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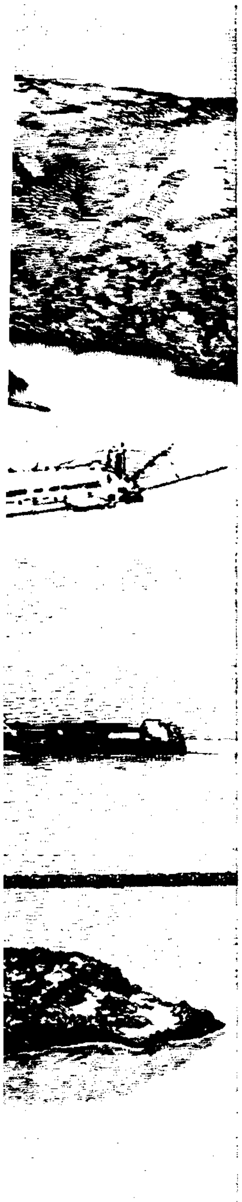

DREDGING RESEARCH PROGRAM

CONTRACT REPORT DRP-92-7

INVESTIGATION OF REAL-TIME DIFFERENTIAL GLOBAL POSITIONING SYSTEM (DGPS) DATA LINK ALTERNATIVES

by

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Final Report

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The Dredging Research Program (DRP) is a seven-year program of the US Army Corps of Engineers DRP research is managed in these five technical areas.

Area 1 - Analysis of Dredged Material Placed in Open Water

Area 2 - Material Properties Related to Navigation and Dredging

Area 3 - Dredge Plant Equipment and Systems Processes

Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems

Area 5 - Management of Dredging Projects

US Army Corps
of Engineers
Waterways Experiment
Station

Dredging Research Program Report Summary

Investigation of Real-Time Differential Global Positioning System (DGPS) Data Link Alternatives (Contract Report DRP-92-7)

ISSUE: Accurate vessel positioning, survey controls, and dredge-travel monitoring are important to many facets of a dredging program, ranging from the planning phase to contract payment as well as including satisfaction of environmental concerns. Presently, the systems used for horizontal positioning of hydrographic survey vessels and dredges require daily calibration with a known point (shore station). The shore stations are extremely expensive and labor intensive to calibrate and maintain. Further, dredging and survey operations are vertically referenced to the vessel performing the work. This reference is continuously in error by short- and long-term sea surface action. Thus surveyors cannot accurately define the datum at a job site.

RESEARCH: Real-time data broadcast systems were considered for the transmission of DGPS data to mobile users. The following types of meter- and decimeter-level broadcast systems were investigated: low- and medium-frequency groundwave systems, high-frequency skywave systems, very-high frequency (VHF) and ultra-high frequency (UHF) systems, and satellite systems. The systems were characterized on the basis of coverage, time delay, amount of development required, cost, and additional manpower requirements.

SUMMARY: Two specific groundwave systems were identified that could be used, and the advantages and limitations of each systems are described. High-frequency skywave systems and VHF and UHF radios and repeaters were found to have promise for both meter- and decimeter-level corrections; various advantages and limitations were enumerated. mobile satellite systems are being developed that could be adapted to Corps use and were mentioned. Major recommendations were included for meter- and decimeter-level DGPS. The findings of this study will be used as background information for planning the later analysis and design phases of the work unit.

AVAILABILITY OF THE REPORT: The report is available through the Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, telephone number (601) 634-2355. National Technical Information Service (NTIS) report numbers may be requested from WES Librarians.

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13. ABSTRACT *(Maximum 200 words)*

This report describes real-time data broadcast systems for the transmission of differential GPS (DGPS) data to mobile users. It considers broadcast systems for the meter level DGPS, which require data rates of 50 to 100 bits per second; and it considers broadcast systems for decimeter level DGPS, which require small-commensurate with operation on a 16-ft skiff. It considers broadcast systems of the following type: low- and medium-frequency groundwave systems; high frequency skywave systems; very high and ultra high frequency systems; and satellite systems. It characterizes these systems on the basis of coverage, time delay, the amount of development required by the U.S. Army Topographic Engineering Center, cost and the number of additional field personnel required. Finally, the report discusses communications for multiple reference station systems.

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PREFACE

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Dredging Research Program (DRP). The work was performed under Work Unit 32479, "Horizontal/Vertical Positioning System based on Global Positioning System Satellite Constellation". Mr. Carl A. Lanigan was Principal Investigator. Mr. M.K. Miles (CE-EP-S) was the DRP Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr. (CERD-C) was the DRP Coordinator for the Directorate of Research and Development, HQUSACE; Mr. E. Clark McNair (CEWES-CD-P), was the DRP Program Manager. Mr. George P. Bonner (CEWES-JV-Z), was the Technical Area Manager. The DRP was assigned to the Coastal Engineering Research Center, Dr. James R. Houston, Director, and Mr. Charles C. Calhoun, Assistant Director.

The work was performed under contract with Worcester Polytechnic Institute. The principal authors were Per K. Enge and Keith Pflieger.

Mr. Frederick Gloeckler was the Contracting Officer's Technical Representative for the U.S. Topographic Engineering Center. Mr. Regis J. Orsinger was Director, Topographic Developments Laboratory; Mr. Peter J. Cervarich was Chief, Surveying Division and Mr. Stephen R. DeLoach was Chief, Precise Survey Branch.

Colonel David F. Maune was Commander and Director, Mr. Walter E. Boge was Technical Director of the U.S. Topographic Engineering Center when this study was accomplished.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

For further information on this work, contact Ms Sally Froge at (703) 355-2819 or Mr. E. Clark McNair, Jr., at (601) 634-2070.

CONTENTS

SUMMARY

This report describes real time data broadcast systems for the transmission of differential GPS (DGPS) data to mobile users. It considers broadcast systems for meter level DGPS, which require data rates of 50 to 100 bits per second (bps); and it considers broadcast systems for decimeter level DGPS, which require 1000 to 2000 bps. The study requires that the mobile terminals be small-commensurate with operation on a 16 foot hydrographic surveying skiff. It considers broadcast systems of the following types: low and medium frequency groundwave systems; high frequency skywave systems; very high and ultra high frequency systems; and satellite systems. It characterizes these systems on the basis of coverage, time delay, the amount of development required by U.S. Army Topographic Engineering Center (TEC), cost, and the number of additional field personnel required. Finally, the report discusses multiple reference station systems.

Section 1

Introduction and Summary

This study seeks and describes radio systems for broadcasting differential corrections from GPS reference stations to small mobile platforms in real time. It considers systems of the following types:

- Low and Medium Frequency (LF and MF) Groundwave Systems
  - Marine radiobeacons
  - Upper MF ground wave broadcast (Sercel)
  - Loran-C communications, Decca Navigator, GWEN
- High Frequency (HF) Skywave Systems
- VHF and UHF Systems
  - VHF/UHF radios and repeaters
  - Television vertical blanking interval
  - Cellular Telephone
  - Special Mobile Radio Systems (SMRS)
  - FM Subcarrier
- Satellite Systems
  - DGPS services (Comsat)
  - Leased space capacity (AMSC)

Among these, the report finds a few systems which are suitable for differential Global Positioning System (DGPS) broadcasts. Some systems provide contiguous United States (CONUS) coverage and some systems must be set up for a specific region. In either case, the report gives coverage estimates. The report also estimates the amount of data latency introduced by the communication system. It gives block diagrams for all of the viable broadcast alternatives, and identifies which of the blocks are currently available, and which require development by the U.S. Army Corps of Engineers (USACE). It gives cost estimates for the equipment required, and it also identifies whether additional field personnel would be required to setup or run the communications equipment.

Some of the broadcast systems described herein are capable of broadcasting meter level DGPS corrections, and others are capable of broadcasting decimeter level corrections. These two applications are now briefly described.

Meter level DGPS systems broadcast GPS code phase corrections to the mobile users. Meter level DGPS achieves accuracies of 4 to 8 meters, where the corrections are valid for 1000 kilometers or so [1]. The data format developed by Special Committee 104 of Radio Technical Commission for Maritime (RTCM SC 104) is well suited; and most importantly, data rates of 50 to 100 bps are adequate. The study seeks techniques which can broadcast data at 50 to 100 bps to users widely dispersed over areas up to 1000 kilometers in radius. It assumes that large transmitters can be used if needed, because a wide area meter level DGPS may be permanent, or nearly so.

Decimeter level DGPS requires the broadcast of corrections to the GPS carrier phase. It achieves accuracies of 0.1 meter, where the corrections are valid for 100 kilometers or so. The data format of RTCM SC 104 may or may not be well suited for this broadcast. Additionally, a decimeter level DGPS system may require "secondary" multiple reference stations in addition to the "primary" reference station. The data from the primary reference station must be broadcast at 1000 to 2000 bps, and it must arrive at the user in real time (less than 1 second delay). Fortunately, the data from the secondary reference stations simply describes the spatial derivatives of ionospheric and tropospheric delay, and only requires a 20 bps data rate. More importantly, it can suffer a 10 second (or perhaps more) data latency. For these reasons, this study assumes that the secondary reference stations telemeter (point to point communication as opposed to broadcast) their data to the primary reference station, which multiplexes the secondary data in with the primary data stream. Multiple reference stations are further addressed in Section 6.

For both meter level and decimeter level broadcasts, the mobile terminals must be small and lightweight, because some will be placed on very small mobile platforms, such as 16' skiffs or small vans. Additionally, the terminals should not severely restrict the turning rate of the mobile platforms. Consequently, the low, medium and high frequency systems considered in this report are required to perform well with short whips on the mobile platforms. Additionally, the satellite systems are required to operate with small "briefcase" style terminals. Large satellite terminals are not appropriate for the mobile user.

Our meter level and decimeter level DGPS broadcast systems are real-time, one-way, data-broadcast networks. They are one-way broadcast networks because the data flows outward from the reference station to the mobiles and no data flows back to the reference station. Both systems are real-time because even though the data is precisely time tagged, it must arrive at the mobile

within a few seconds. Decimeter level systems can tolerate a greater delay than meter level systems. In fact, they can tolerate data latencies of 1 to 10 seconds.

This requirement on the age of the corrections is unfortunate, because it precludes the use of a large number of packet switch networks which are being developed for data traffic. Additionally, it limits the amount of forward error correction and interleaving which can be used to insure the integrity of the information or extend the range of the broadcast. In short, a complex tradeoff exists between data latency, data reliability and range. The proper solution to this tradeoff depends on the details of the particular link under consideration, and no universal solutions exist.

1.1 Summary of Findings

The main findings of this report are summarized in Tables 1.1 and 1.2. These tables are discussed in the following paragraphs.

Section 2 of this report considers DGPS broadcast systems which use groundwave propagation. Such systems are attractive, because groundwave propagation affords coverage beyond the radio horizon, where the DGPS corrections themselves are still valid. As such, groundwave systems are well "matched" to the DGPS application. Section 2 finds two specific groundwave systems which could be used by USACE.

First, the marine radiobeacon system which is being developed by the U.S. Coast Guard (USCG) is well suited for providing meter level corrections in coastal areas. This system adds a digitally modulated subcarrier to transmissions from existing marine radiobeacons, which operate in the 285 to 325 KHz band. If the system is fully deployed, it will cover most of the U.S. coast. Additionally, the broadcast will cover 20 to 100 kilometers inland. Conceivably, USCG could ask USACE to share in the cost of the transmitter network. However, USACE would not need to develop any hardware, software or interfaces. Appropriate receivers will soon be available at a cost of less than $3000, and the price is expected to drop significantly when volume production begins. However, the data delay may be large compared to USACE's requirements, and this concern deserves further investigation. Additionally, the radiobeacons will not serve USACE applications far from the coast, nor will they serve the decimeter level applications.

Second, another groundwave system for coastal service is being developed by Sercel Inc. This system uses frequency diversity to achieve reliable communication in the presence of the fading and atmospheric noise which characterize the upper MF band. In fact, the Sercel system broadcasts one carrier in the upper MF band, and one carrier in the lower HF band.

Sercel has used this broadcast system to create a complete integrated meter level DGPS product. This product has a range of 700 kilometer overwater and approximately 100 kilometers overland. The base station, which includes a reference receiver and radio transmitter, costs around $140,000. The mobile unit, which includes a GPS receiver and an MF/HF receiver, costs between $15,000 and $30,000. If USACE is content to use the Sercel GPS receivers, then they would not need to develop any hardware to use this system. However, if they wished to integrate other GPS receivers, then new interfaces would be required. In any event, USACE would have to deploy field personnel to setup and tend the base station/transmitter. Additionally, it may have significant problems obtaining licenses for the two required radio channels.

This Sercel system could be modified at modest cost to accommodate the higher rate decimeter level corrections. Once again, additional modifications would be needed if GPS receivers other than those manufactured by Sercel were to be used. A decimeter level broadcast using the Sercel concept would have an overwater range of around 400 kilometers, and an overland range of approximately 50 kilometers.

Section 3 shows that HF skywave systems have promise for both meter and decimeter level corrections. Importantly, such systems can be deployed for overland coverage or overwater coverage. Two transmitters can be used to broadcast meter level corrections to all users in a circle with 1000 kilometer radius. These transmitters would be placed 500 kilometers <u>outside</u> of the circle and beam their corrections back into the coverage area. One transmitter can broadcast decimeter level corrections to all users in a circle with 100 kilometer radius. Once again, the transmitter would be placed outside of the circle and beam the corrections into the coverage area.

The HF system would have to use frequency diversity of some sort to combat fading and interference. If USACE has enough available channels, then the HF system could send 3 or 4 narrowband signals simultaneously. A similar concept has demonstrated very high reliability in "push to talk" applications for the U.S. Customs Service. Alternatively, if USACE does not have enough available HF channels, then spread spectrum concepts could be considered.

Comm. Alternative	CONUS Coverage Avail.> 97%	Failure Mechanisms	Time Delay (sec)	TEC Development	Cost	Field Personnel	Comments
Radiobeacons 285-325 KHz 405-490 KHz	90% of Coast 30 km Inland	Atmos.Noise Man-made Int.	4	None	Interagency Cost Sharing? Rcv: $3K	None	Under development 8/90 Montauk Pt. Inland difficult
Upper MF Groundwave (Sercel)	Overwater: 700 km. Overland: 100 km	Atmos.Noise Man-made Int.	4	None	Ref/Tmtr: $140K GPS.MF Rcv: $15K	Tmtr.	Licenses
High Frequency Skywave 6.0-14.0 MHz	1000 km radius	Man-made Int. Sunspot Fading Absorption	1-5	Signal Design Combiner Interfaces	Tmtr: $100K Rcv: $10K	Tmtr.	Avail. Channels U.S. Customs Spread Spectrum Sercel and Collins
VHF/UHF LOS 30 MHZ-3GHz	Radio Horizon	Shadowing Fading	0.5-2	Interfaces	Tmtr:$1K Rcv: $1K Repeater: $2K	Tmtr. Repeater	Licenses Existing Nets.
VHF/UHF DGPS Package (Sercel)	Radio Horizon	Shadowing Fading	0.5-2	None	Ref/tmtr:$50K GPS/UHF rcv: $15K Repeater: ?	Tmtr. Repeater	Licenses Existing Nets.
TV VBI (PBS Datacast)	70% of land, 80% of coast	Shadowing Fading	2	Mobile tests Interfaces	Conus, 1200 bps $30K/month Local service avail.	None	
Satellite DGPS Service (Comsat)	100%		2	None	$11K/month/ mobile Quantity discounts Std A: $50K	Shore	Van within LOS Std C under dev.

Table 1.1: Viable Broadcast Alternatives For Meter Level DGPS (50 to 100 bps)

Comm. Alternative	CONUS Coverage *Avail > 97%*	Failure Mechanisms	Time Delay (sec)	TEC Development	Cost	Field Personnel	Comments
Upper MF Groundwave (Sercel)	Overwater: 410km Overland: 50km	Atmos. Noise Man-made Int.	4	Modify equip. for higher data rate	Ref/Tmtr: $140K GPS/MF Rcv: $15K	Tmtr.	Licenses
High Frequency Skywave 6.0-14.0 MHz	100 km radius	Man-made Int. Sunspot Fading Absorption	1-5	Signal Design Combiner Interfaces	Tmtr: $100K Rcv: $10K	Tmtr.	Avail. Channels US Customs Spread Spectrum Minimize Data Rate Sercel *and Collins*
VHF/UHF LOS 30 MHz-3GHz	Radio Horizon	Shadowing Fading	0.5-2	Interfaces	Tmtr: $1K Rcv: $1K Repeater: $2K	Tmtr. Repeater	Licenses Existing Nets.
VHF/UHF DGPS Package (Sercel)	Radio Horizon	Shadowing Fading	0.5-2	None	Ref/tmtr: $50K GPS/VHF rcv:$15K Repeater: ?	Tmtr. Repeater	Licenses Existing Nets
TV VBI (PBS Datacast)	70% of land 80% of coast	Shadowing Fading	2	Mobile tests *Interfaces*	Conus, 2400 bps $33K/month Local service avail.	None	
Satellite Dedicated channel (AMSC)	100 %		2	Interfaces	25% Conus 2400 bps $7.5K/month Terminal: $4K	None	3 to 4 years

Table 1.2: Viable Broadcast Alternatives For Decimeter Level DGPS (1000 to 2000 bps).

The cost of an HF transmitter can be as low as $30,000 and USACE may already have appropriate transmitters in storage. However, 3 or 4 such transmitters would be required to broadcast 3 or 4 narrowband signals. A single channel HF receiver costs $2000 or less, and 3 or 4 such receivers would be required for a multiple frequency broadcast. Field personnel would have to setup and tend the 1 or 2 HF transmitters which would be remote from the reference station. However, the mobile equipment should not require dedicated or highly trained personnel.

The HF system requires a study to design the signal, develop the interface between the reference station and the transmitter, to develop the equipment to combine the outputs from the different receivers, and to develop the interface with the mobile GPS receiver.

As described in Section 4, VHF and UHF radios can certainly provide meter and decimeter level DGPS data to users within line of sight of the transmitter. The maximum baud rate of a VHF or UHF digital data link is constrained in practice by the channel license, which usually corresponds to a voice bandwidth of 25 KHz. Occasionally, splinter channels of 12.5 KHz are used. The necessary VHF and UHF equipment is shown in block diagrams in Section 4, and the cost of such systems is extremely modest. Additionally, Sercel manufacturers a complete VHF/UHF DGPS system for overland use to complement their MF system. The base station includes a reference receiver and a VHF/UHF transmitter, and sells for $50K. The mobile station includes a DGPS receiver and a VHF/UHF receiver, and sells for $15K to $30K depending on which GPS receiver is used.

VHF and UHF repeaters can be used to provide coverage over larger areas. Indeed, the Wilmington District already has a VHF network for voice communications which covers most of the state, and may well be suited for DGPS broadcast. However, data transmission is more fragile than voice communication, and shadowing or fading may cause a high DGPS error rate. Data transmission should be tested, and if the connection is unreliable then modems with error correction should be investigated.

A digital VHF/UHF transmitter costs $600 to $1000; the corresponding receiver also costs $600 to $1000; and repeaters cost around $2000. If USACE does not purchase integrated VHF/UHF DGPS communication systems, then they will have to develop the interfaces between the reference receiver and the transmitter, and those between the receiver and the mobile DGPS receiver. Field personnel would have to be deployed to setup and perhaps tend the VHF transmitters and repeaters. However, no dedicated personnel should be required at the receivers.

The Public Broadcasting System (PBS) has a wide area

broadcast system for data, which covers about 60% of CONUS. This system is called National Datacast and uses the vertical blanking interval (VBI) of PBS TV broadcasts. A nationwide broadcast of 2400 bps costs $33,000 per month, and could be used to carry 1 or 2 decimeter level signals as well as several meter level signals. Additionally, the PBS system can be used to broadcast data from one or several TV stations. The price of such a local service is significantly lower than a nationwide broadcast. To use PBS, USACE would have to develop interfaces to the fixed and mobile GPS receivers. Additionally, the PBS broadcast is only available 18 hours a day, and no extensive mobile tests have been conducted.

Section 5 considers satellite systems for the broadcast of DGPS data. Indeed, many mobile satellite companies are providing, or are planning to provide a DGPS service. These include John Chance through their Starfix system; the Communications Satellite Corporation (COMSAT) through the Inmarsat system; and DGPS Inc. of Houston Texas in collaboration with Qualcomm. The DGPS service costs $200 to $500 per day per mobile and includes the reference station and mobile GPS receiver. Clearly, this "per user per day" is high for many USACE applications, but they may be able to negotiate much more favorable agreements based on large scale use of the system. However, the current DGPS services all require satellite terminals, which are too large for use on small boats or in small vehicles. Moreover, some of the terminals cannot track the satellite during the rapid turns that small vessels or vehicles can execute.

Mobile satellite systems which can communicate with smaller terminals are being developed. For example, COMSAT is studying a DGPS service which could communicate to omnidirectional antennas like the ones used by the Inmarsat C service. In 3 or 4 years, AMSC will launch a satellite which can communicate with small terminals, and approximate monthly rates for a continuous broadcast from this satellite are shown in Table 1.2.

Section 6 discusses communications between the monitor reference stations and the master reference station. Monitor reference stations are required for decimeter level DGPS. However, they only need to send data at 20 bps and a data latency of 10 seconds is tolerable. Consequently, the data from the monitor reference stations should be sent to the master reference station, where it would be multiplexed onto the broadcast from the master reference station to the mobiles. Such a scheme is efficient, because it is much easier to deploy point to point communication systems than broadcast systems.

If possible, the monitor reference stations should be connected to the master reference stations using a phone line. VHF/UHF radios can be used to complete the connection if the

monitor reference station is not collocated with a telephone.

Finally, Section 7 describes the licensure procedure which applies for all new radio systems.

1.2 Recommendations

Our major recommendations to TEC are:

Meter Level DGPS Along the Coast: Support and participate in the USCG's development of the DGPS/radiobeacon system. In particular, participate in the field trials of this system. This system can serve many meter level applications in coastal regions. If not, then VHF and UHF radios will provide coverage out to 40 miles. Indeed, the Sercel VHF/UHF DGPS system may be a good investment depending on the suitability of the GPS receiver and reference station. If VHF/UHF radio is inadequate, then the Sercel medium frequency groundwave system would most certainly provide adequate coverage (at greater cost).

Decimeter Level DGPS Along the Coast: Even at the higher data rate, VHF and UHF radios will provide coverage out to 40 miles or so. If this coverage is not adequate, then Sercel may modify their MF groundwave system to handle the higher data rate. Alternatively, if a PBS TV station is well located, then lease capacity on the National Datacast System. Finally, HF radio can be used, but this alternative still requires significant development by TEC.

Decimeter and Meter Level DGPS Inland: VHF or UHF radio may be able to provide adequate range overland depending on the terrain. Repeaters can be used to extend coverage into the application area. Once again, the Sercel VHF/UHF DGPS system may be a good investment, or a PBS TV station may provide a cost effective solution. HF radio is capable of broadcasting with adequate reliability, but this approach requires development by TEC. In other words, no "off-the-shelf" HF solutions exist. TEC should develop an HF system for DGPS if the above described alternatives are inadequate.

Satellite Systems for Meter Level DGPS: A variety of meter level DGPS satellite services will be available in the near future. If the mix of terrestrial radio solutions described above is not satisfactory and the large satellite terminals are acceptable, then USACE could try to negotiate an agency wide subscription to one of the current satellite DGPS services.

Satellite Systems for Decimeter Level DGPS: USACE should definitely participate in meter and decimeter level trials of the AMSC mobile satellite system. These trials would be sponsored by NASA.

Section 2

Low and Medium Frequency Groundwave Systems

2.1 Overview

This Section considers the use of low and medium frequency (LF and MF) radio systems to broadcast DGPS data. Indeed, these bands are attractive, because they are characterized by groundwave propagation, which can reliably carry signals well beyond the radio horizon. The next section contains a brief LF and MF broadcast study, which provides the basis for the specific LF and MF systems which are considered in sections 2.3 through 2.8.

2.2 Low and Medium Frequency Broadcast Study

LF and MF groundwaves propagate to distances beyond the radio horizon. Therefore LF and MF systems are attractive for DGPS, because the differential corrections are valid for ranges beyond line of sight. However, the actual range of a groundwave broadcast depends on the following factors:

Effective Ground Conductivity: Groundwaves propagate with less loss over surfaces with high conductivity such as seawater. They are attenuated more quickly as they travel across media with poor conductivity like mountainous regions or urban areas.

Carrier Frequency: As carrier frequency decreases, groundwaves propagate with less loss. In other words, if two antennas are radiating the same amount of power, then the field strength of the signal with the lowest frequency will be larger.

Radiated Power: As frequency decreases, the efficiency of antennas decreases, because they become electrically short. In other words, if an antenna with fixed length is connected to a transmitter with fixed power, then the radiated power will decrease rapidly as the frequency is decreased.

Atmospheric Noise: The range of a broadcast system is not determined by the received signal strength. Rather it is determined by the received signal to noise ratio. Atmospheric noise is caused by lightning and is the predominant noise source at LF and MF frequencies. Atmospheric noise power decreases with increasing frequency.

This section describes a study which computed the range of various LF and MF broadcast systems. The study assumes that a signal to noise ratio (SNR) of 5 dB is required for reliable transmission of digital data. The range at which the SNR dropped to 5 dB is computed for the following carrier frequencies: 100 KHz, 180 KHz, 300 KHz, 1 MHz, and 2 MHz. The range is also

computed for propagation over seawater, land with "good" conductivity, and land with "poor" conductivity. The range computation assumes that the atmospheric noise level is equal to the noise which is exceeded only 10% of the time in the noisiest region in CONUS. It assumes that the transmitting antenna is 50 meters tall, and that if this height is less than a quarter wavelength, then the antenna is top loaded to increase efficiency. Finally, the computation was made for a bit rate of 50 bps (meter level DGPS) and 2000 bps (decimeter level DGPS), and a variety of transmitter powers.

A generic set of curves for this study are shown in Figure 2.1, which shows field strength versus range for 100 KHz signals over seawater. In fact, it shows groundwave field strength, typical nighttime skywave field strength, and typical daytime skywave field strength. It uses a radiated power of 0.03 x 10,000, because the efficiency of 50 meter antennas at 100 KHz is only 3 percent. Figure 2.1 also shows the upper decile atmospheric noise field strength in a 200 Hertz bandwidth for the worst case time block in CONUS. As shown, the groundwave to atmospheric noise SNR falls to 5 dB at a range of 500 kilometers.

Similar curve sets were generated for the other frequencies and other ground conductivities. These curves were used to derive Tables 2.1 and 2.2, which summarize the performance of groundwave broadcast systems in the presence of atmospheric noise. Table 2.1 gives broadcast range for the meter level DGPS signal, which only requires a noise bandwidth of around 50 Hz. As shown, the lower frequency systems do perform best overland, because of the reduced attenuation rate of groundwave overland. However, the higher frequency systems work better oversea, because of the lower noise levels and greater antenna efficiencies.

Table 2.2 gives broadcast range for the decimeter level DGPS signal, which requires a noise bandwidth of around 2000 Hz. As shown, the range of all the systems is reduced relative to those in Table 2.1, because of the greater noise bandwidth. However, the lower frequency systems still perform best overland, and the higher frequency systems still work better oversea. Tables 2.1 and 2.2 will be referenced in the next 3 sections, which discuss specific groundwave systems.

2.3 Radiobeacons

Marine and aeronautical radiobeacons provide position fixing information to users worldwide. A single radiobeacon can be used to estimate the bearing from the user to a known location. Alternatively, two radiobeacons can be used to estimate two bearings, and if the crossing angle is large enough these two bearings can be used to estimate user position. The bands from

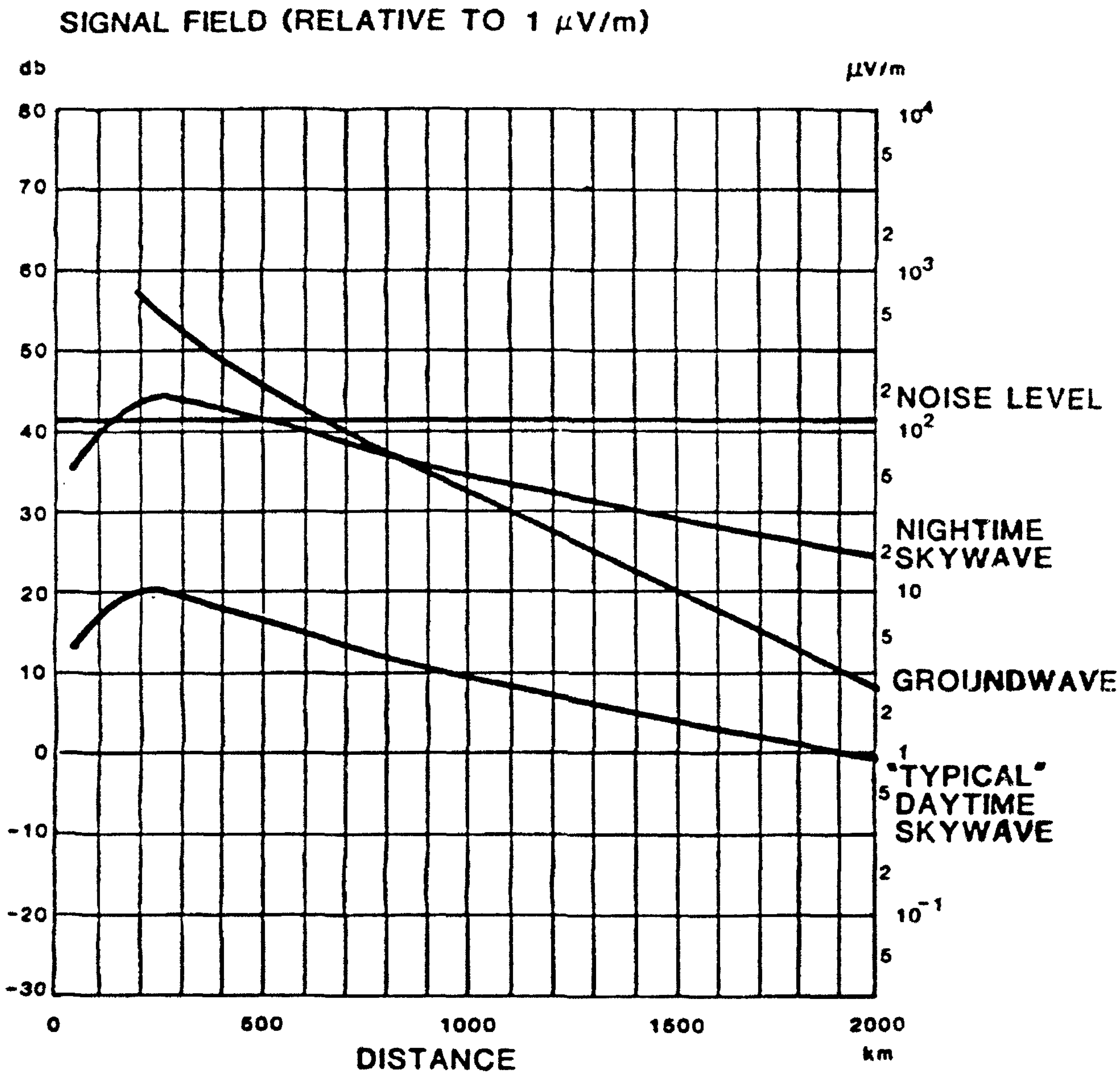

Figure 2.1: Groundwave, Typical Nightime Skywave, Typical Daytime Skywave and Noise Field Strength For 100 KHz Over Seawater as a Function of Distance.

Frequency and Power	Power Radiated	Sea	Good Land	Poor Land
100KHz 10 KWatts 1 KWatt	 300 W 30 W	 700 km 350 km	 640 km 320 km	 420 km 220 km
180 KHz 1 KWatt	 170 W	 450 km	 380 km	 200 km
300 KHz 100 Watts 10 Watts	 32 W 3.2 W	 350 180	 260 130	 70 40
1 MHz 1 KWatt	 790 W	 800	 200 (*,0)	 50 (*,0)
2 MHz 1 KWatt	 790 W	 650	 130 (*,300)	 50 (*,0)

Table 2.1: Range (in km.) of LF and MF Radio Systems for Meter Level DGPS (BW_{noise} = 50 *Hz*). The required SNR is 5.0 dB. The transmitter antenna is 50 meters tall, and is top loaded if 50 meters is less than a quarter wavelength. The ranges denoted with a "*" are for typical daytime skywave (availability around 50%).

Frequency and Power	Power Radiated	Sea	Good Land	Poor Land
100KHz 10 KWatts 1 KWatt	 300 W 30 W	 220 km 80 km	 220 km 80 km	 150 km 50 km
180 KHz 1 KWatt	 170 W	 130 km	 100 km	 60 km
300 KHz 100 Watts 10 Watts	 32 W 3.2 W	 70 20	 50 20	 20 10
1 MHz 1 KWatt	 790 W	 500	 150 (*,0)	 10 (*,0)
2 MHz 1 KWatt	 790 W	 410	 80 (*,0)	 10 (*,0)

Table 2.2: Range (in km) of LF and MF Radio Systems for Decimeter Level DGPS (BW_{noise} = 2000 *Hz*). The required SNR is 5.0 dB. The transmitter antenna is 50 meters tall and is top loaded if 50 meters is less than a quarter wavelength. The ranges denoted with a "*" are for typical daytime skywave (availability around 50%).

285 to 325 KHz and from 405 to 415 KHz are for marine radiobeacons (primary allocation) and aeronautical radiobeacons (secondary). The band from 325 to 405 KHz is for aeronautical beacons (primary).

USCG is considering using the marine radiobeacons to broadcast meter level DGPS data to coastal users. A DGPS/radiobeacon broadcast network is attractive for many reasons. First of all, the beacons are widespread, and so the DGPS capability could become widely available at low cost. In fact, the International Association of Lighthouse Authorities [2] has international responsibility for the marine radiobeacons, and they are hoping to establish an international standard for the DGPS/radiobeacon signal.

The beacons are also well located for some known DGPS applications. For example, USCG is interested in using DGPS for harbor and harbor entrance navigation [3], and radiobeacons are frequently located near the critical harbors. Finally, user equipment is inexpensive to design and manufacture at medium frequencies. In fact, the cost of a DGPS/radiobeacon receiver in modest quantities will most certainly be less than $1000.

Importantly, the DGPS signal can be added to the radiobeacon signal such that it does not interfere with the vast majority of marine and aviation direction finding equipment, which currently use the radiobeacons. The details of this interference analysis are presented in [4] and supporting measurements are described in [5].

The range of DGPS/radiobeacon depends on whether or not forward error correction is used. With stronger codes, the receiver can operate in lower signal to noise ratios. Unfortunately, the introduction of error correction also increases the DGPS delay, so a tradeoff exists between broadcast range and delay. Figures 2.2 and 2.3 show the average time between meter level DGPS updates as a function of range from the radiobeacon, the data rate and degree of error correction.

Figure 2.2 shows the delay for uncoded systems. As the baud rate is increased from 50 to 400 baud, the delay decreases provided the user is close to the radiobeacon, and the signal to noise ratio is good. However, as the user moves away from the radiobeacon, the signal to noise ratio degrades and the lower baud rate systems enjoy smaller delays. At short ranges, the delay varies from 4 to 14 seconds as the baud rate goes from 400 to 50 baud.

Figure 2.3 shows delay versus range for DGPS/radiobeacons with forward error correction. As shown, error correction increases the delay for small ranges, but decreases the delay for

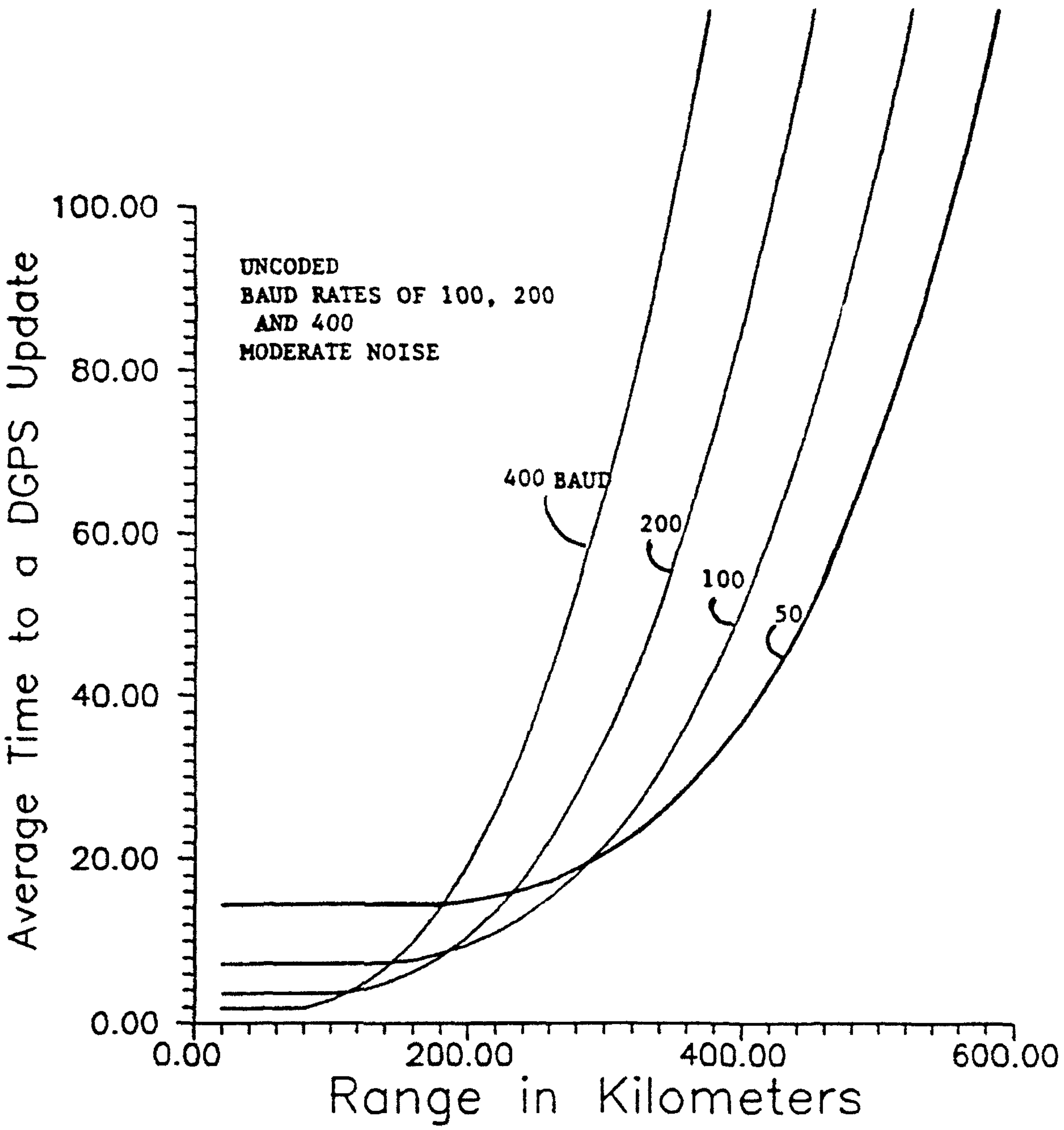

Figure 2.2: Average Message Delay Versus Range For Uncoded DGPS/Radiobeacon Systems in Moderate Atmospheric Noise. Delay is defined as the time between the receipt of a message by the radiobeacon to the delivery of that message or a subsequent one to the user.

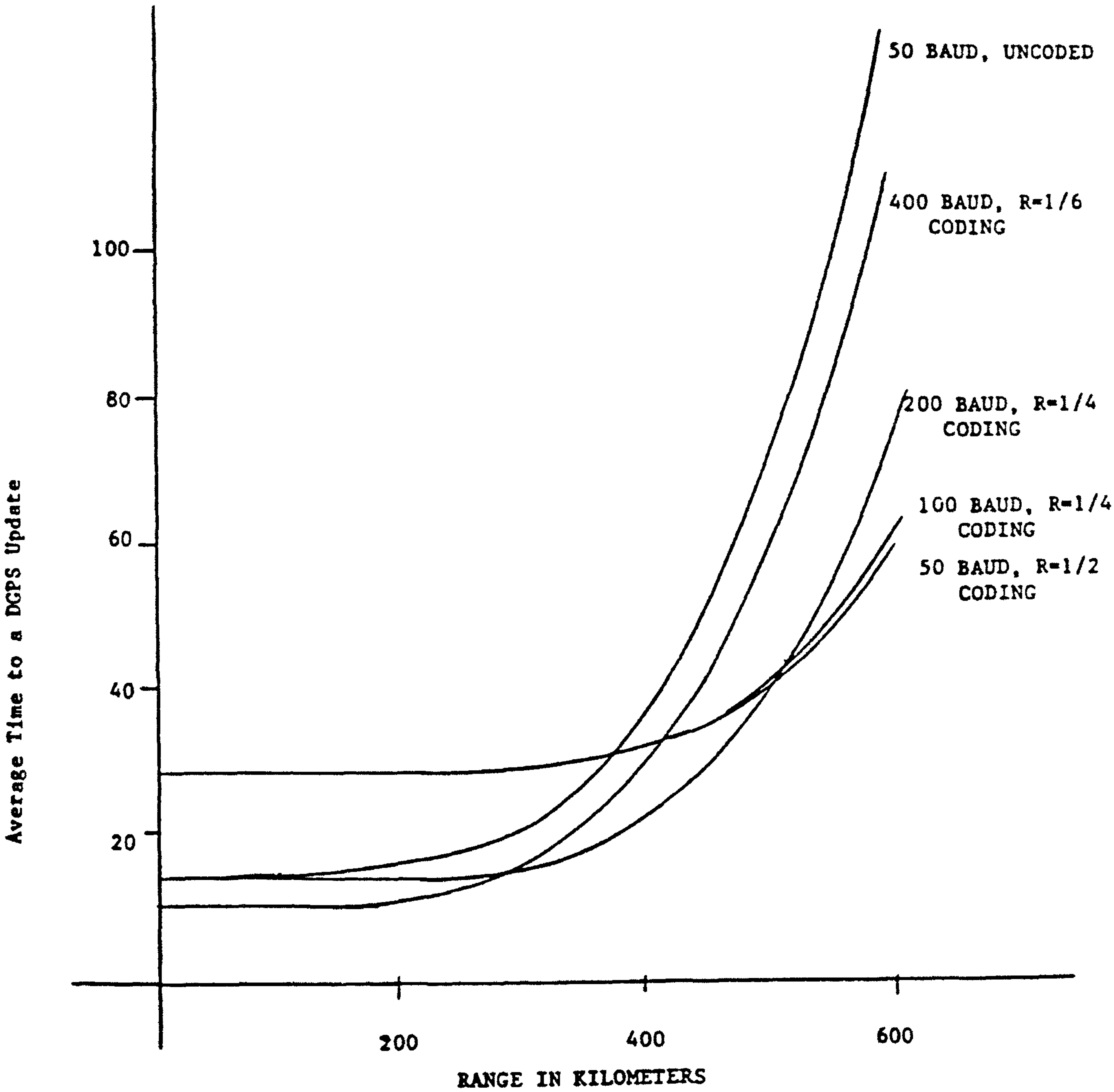

Figure 2.3: Average Message Delay Versus Range For Uncoded and Coded DGPS/Radiobeacon Systems in Moderate Atmospheric Noise. Delay is defined as the time between the receipt of a message by the radiobeacon to the delivery of that message or a subsequent one to the user.

large ranges. The delay for 200 baud with $R=1/4$ coding is approximately 14 seconds for all ranges out to approximately 350 kilometers.

Figure 2.4 is a block diagram of a DGPS/Radiobeacon broadcast system. As shown, the DGPS reference station would be connected to the radiobeacon transmitter site via a standard modem and phone line. The forward error correction and MSK modulator will be available as standard inexpensive units from Magnavox by the Summer of 1991. The transmitter is the standard radiobeacon manufactured by Nautel or Amplidan.

Figure 2.4 also shows the DGPS/radiobeacon receiver, which will also be available as a standard unit from Magnavox by the summer of 1991. It will cost around $3000 initially, and the price is expected to drop significantly as volume production begins. The receiver will provide an RTCM data stream to the DGPS receiver. If Magnavox reference stations and DGPS receiver are used, then the interfaces shown in Figure 2.4 will not be required. Otherwise, USACE may have to provide some interfaces.

In summary, marine radiobeacons are well suited for the broadcast of meter level DGPS corrections in coastal areas. We recommend that USACE support USCG development of DGPS/ radiobeacons.

Unfortunately, the extension of DGPS/radiobeacon coverage inland may be very difficult. Away from the coast, aeronautical radiobeacons, which are known as non-directional beacons (NDBs), occupy the 285-325 KHz band and the 405-415 KHz band. The vast majority of these beacons have much smaller range then the marine radiobeacons, because they broadcast less power and because the groundwave does not propagate as well overland (see Table 2.1 and 2.2). Additionally, the direction finders used by aviators are more sensitive to interference, so it may be more difficult to demonstrate that a digitally modulated subcarrier does not interfere with the direction finding function.

Additionally, the broadcast of <u>decimeter</u> level (high rate) DGPS information on radiobeacon subcarriers may not be fruitful. First, the available bandwidth of the DGPS/radiobeacon is significantly less than 1000 Hz. Consequently, minimum shift keying could not be used and TEC would have to design a new signal and develop a new receiver. Second, the increase in data rate greatly reduces the range of the DGPS signal. As shown in Table 2.1, if 100 Watts of meter level information is transmitted, then the oversea range is 350 kilometers. However as shown in Table 2.2, if 100 Watts of decimeter level information is transmitted, then the oversea range is only 70 kilometers, which is not much greater than a VHF or UHF radio could achieve. If the data rate for decimeter level corrections

RADIOBEACON DATA LINK

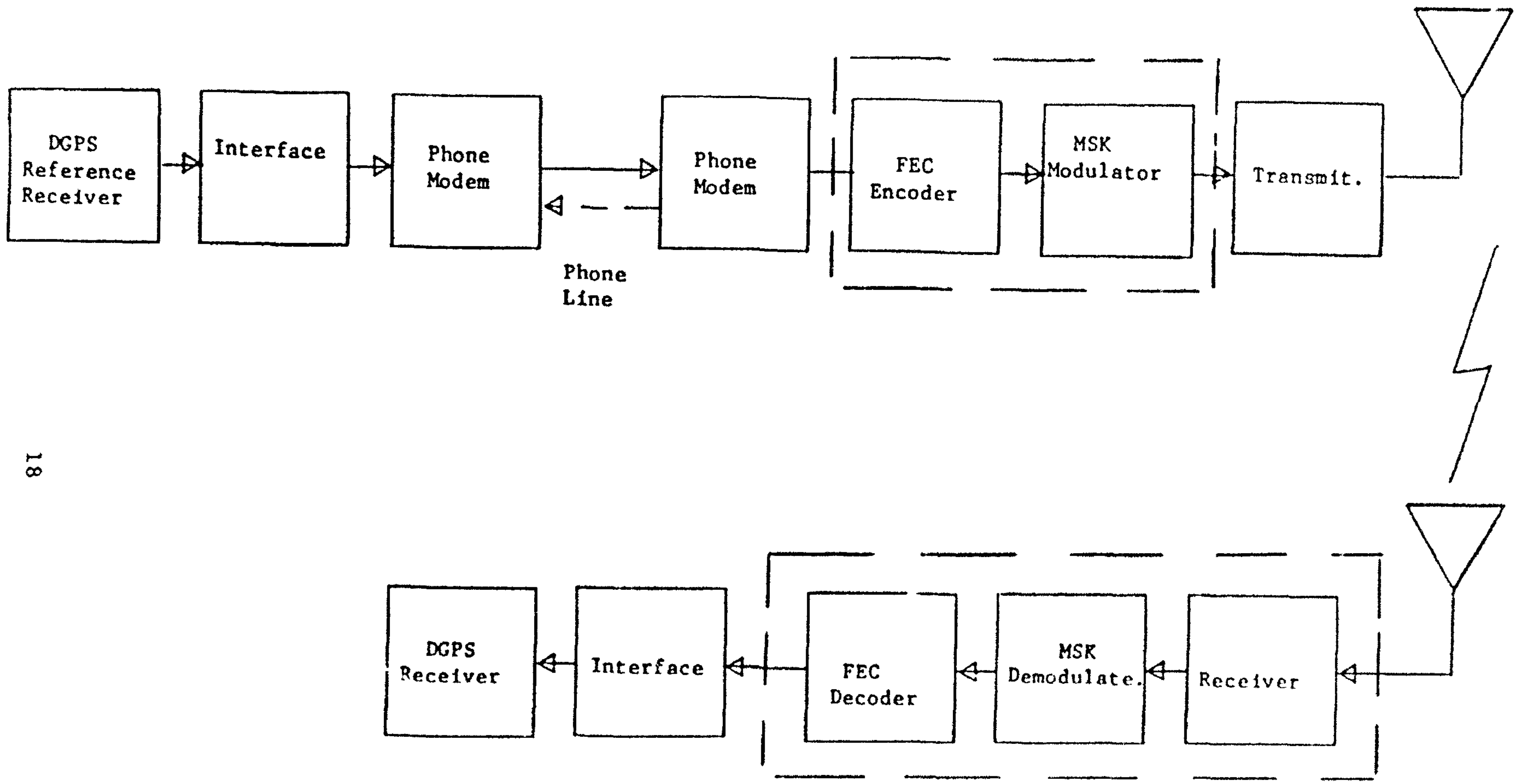

Figure 2.4: Block Diagram of DGPS/Radiobeacon Data Link.

is reduced to 400 bps, then minimum shift keying could be used and the marine radiobeacons may be helpful.

2.4 Medium Frequency Groundwave (1.5 TO 4.0 MHZ)

A second important and attractive groundwave system for the broadcast of meter level DGPS data has been developed by Sercel [6]. This system uses groundwave propagation in the upper portion of the MF band and the lower portion of the HF band. In fact, it transmits at two frequencies simultaneously to achieve diversity against outages caused by multipath fading or atmospheric noise bursts. Typically, the Sercel system uses the frequencies 1.6 and 3.5 MHz, but these can be adjusted in accordance with which frequencies are available in a given application area. The Sercel transmitters can send signals anywhere in the 1.6 to 30 MHz range.

As suggested by Table 2.1, this system achieves excellent range over seawater. In fact, Sercel conservatively specifies their range as 700 kilometers. The range over "good" land is 100 kilometers, but the range over poorly conducting land can be significantly less.

The time delay for the Sercel system is depicted in Figure 2.5 [6]. This time delay data was measured over a 380 kilometer link from Quiberon to Portsmouth, which is a high noise area. As shown, if the dual frequency system is used, then the delay is less than 4 seconds 68% of the time and it less than 7 seconds 95% of the time.

Figure 2.6 is a block diagram of the Sercel MF groundwave system. The cost of complete integrated reference station with reference GPS receiver, two transmitters, and two antenna systems is $140,000 [7]. The cost of the complete receiving system with a Sercel 53 or 103 receiver and a dual frequency receiver is $15,000. The cost of a complete receiving system with a Sercel 104 receiver is $30,000. Importantly, TEC would not need to develop any new equipment, because this system is a complete integrated package. If TEC wished to use receivers other than the Sercel 53, 103 or 104, then new interfaces may well be required.

Field personnel would be required to setup and tend the transmitters, but no other personnel would be required to run the communications equipment.

So far, Sercel has sold 8 or 9 of these meter level DGPS systems, which use MF broadcast. In addition, they feel that the system could be inexpensively modified to accommodate the higher data rates required for decimeter level DGPS. As shown in Table 2.2, the range over water for a decimeter system would still be several hundred kilometers.

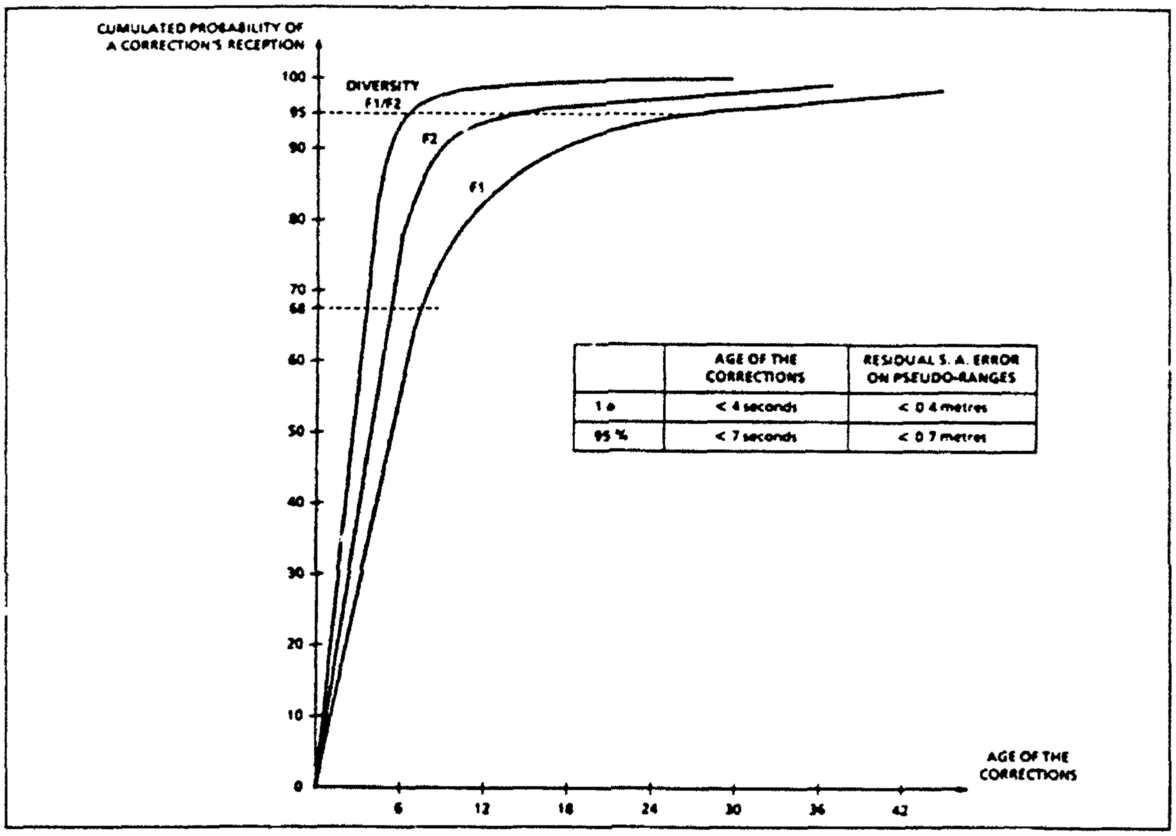

Figure 2.5: Average Message Delay For a Sercel MF Groundwave Link From Quiberon to Portsmouth.

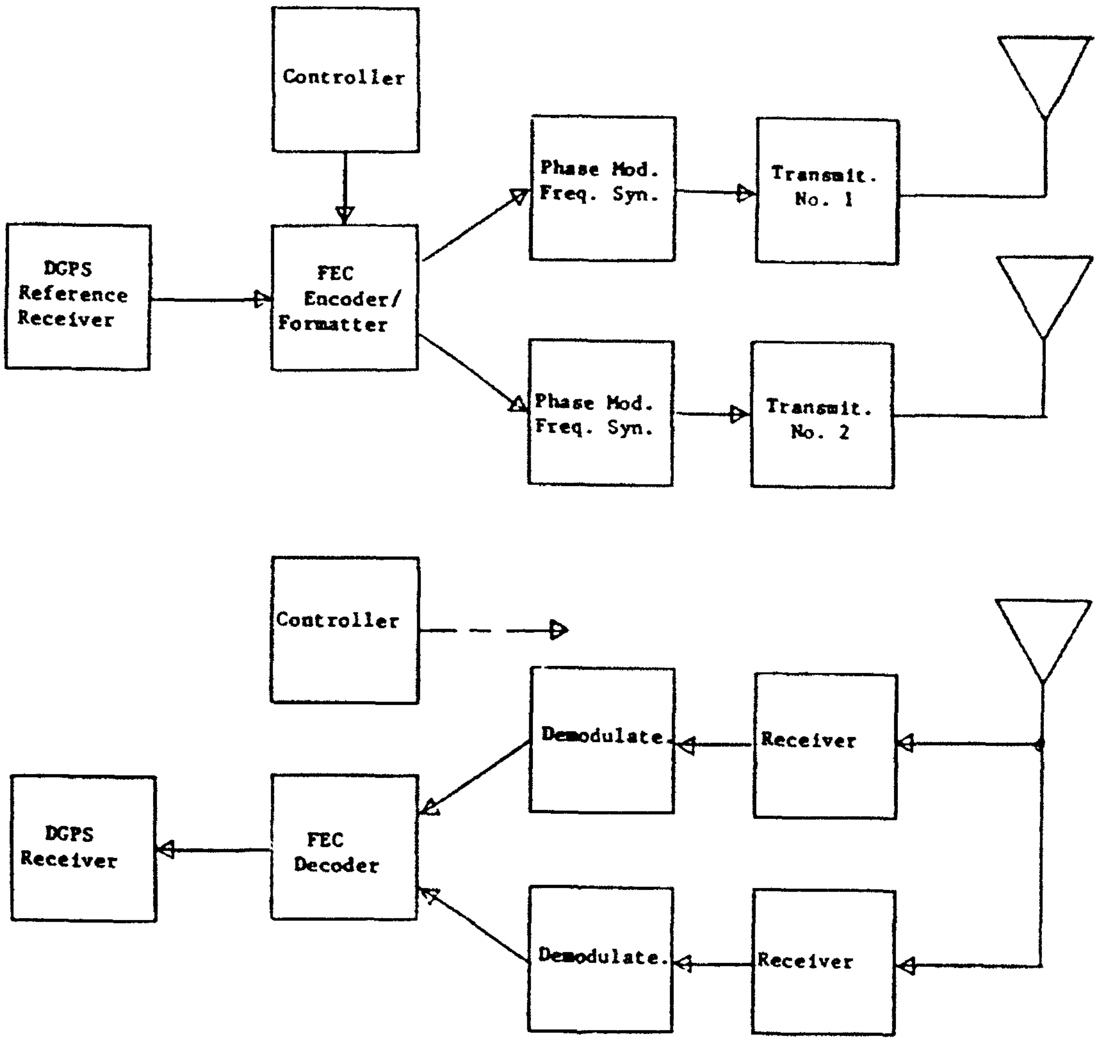

Figure 2.6: Block Diagram of Sercel's Medium and High Frequency Groundwave System .

Unfortunately, the overland performance of a MF/HF groundwave system would be poor (for meter level or decimeter level), because of the large attenuation of the groundwave overland. However, HF skywave systems are discussed in the next section, and they may provide the desired performance overland. Moreover, the Sercel transmitter might be a good building block for a multiple frequency HF skywave system.

2.5 Loran-C, Decca Navigator, and GWEN

This brief section discusses three likely candidates for groundwave broadcast of DGPS; Loran-C, Decca Navigator and the Ground Wave Emergency Network (GWEN).

Loran-C is a radionavigation system, which provides positioning service to nearly a million maritime, airborne and terrestrial users throughout most of the Northern Hemisphere. Loran transmits synchronized signals from a network of terrestrial transmitters and these signals occupy the radionavigation band from 90 to 110 KHz.

Multiple Loran signals can be received at every location in CONUS, and these signals have a latent but proven communication capability. Unfortunately, the communication capacity is only around 20 bps, unless the Loran signal format is significantly altered. Twenty bps is inadequate for differential GPS unless Selective Availability (SA) is discontinued. However, if SA is shut off, then Loran communications may be an ideal method to broadcast meter level DGPS data.

Decca Navigator is another radionavigation system, which serves position fixing applications at sea, on land and in the air. Like Loran, Decca counts on the phase stability of the low frequency groundwave, and it also broadcasts signals from a network of synchronized terrestrial transmitters. These signals occupy the radionavigation bands from 70 to 90 KHz and 110 to 130 KHz. Consequently, Decca (like Loran) enjoys excellent propagation overland and oversea (see Tables 2.1 and 2.2). In contrast to Loran, the worldwide use of Decca is declining; in fact Decca is not used at all in North America.

Decca also has a latent communication capability, but the capacity is less than that for Loran. Even though Decca is no longer used in North America, the bands from 70 to 90 KHz and 110 to 130 KHz are heavily used by the U.S. Navy. Consequently, it would be difficult to establish a new dedicated DGPS service in these bands.

Finally, GWEN is currently being deployed by the U.S. Air Force, and is designed to provide highly reliable communications over CONUS in the event of a nuclear attack. GWEN includes 96 broadcast stations nationwide. It operates at a carrier

frequency of 180 KHz, and uses ground wave propagation to achieve CONUS coverage even during high atmospheric noise conditions.

Unfortunately, GWEN is not suitable for DGPS broadcast. First, its throughput is only 40 bps. Second, it is designed to prevent hostile forces from entering misleading information into the network (anti-spoof). As such, it does not readily accept any outside information source (like DGPS) even during peacetime. Finally, the user equipment is very expensive. It has a high non-recurring cost, because the user equipment includes a cryptographic module. It also has a high recurring cost, because the cryptographic key must be replaced periodically.

Section 3

High Frequency Skywave Systems

3.1 Overview

High Frequency (HF) data links may also be useful for broadcasting DGPS messages over the area for which the corrections are applicable. HF communication systems lie in the range from 3-30 MHz, and have many properties that allow transmission at far greater distances than line of sight (LOS) communication systems. There are, however, many factors affecting performance that must be considered when using HF systems.

The remainder of this section describes the requirements for meter and decimeter level HF broadcast systems, and Section 3.2 describes the HF communication channel in general. Section 3.3 describes a software simulation package for HF communications provided by the Naval Ocean Systems Center (NOSC). This package is used in Sections 3.4 and 3.5 to analyze specific HF broadcast systems for the meter and decimeter applications. Finally, Section 3.6 describes the concept of frequency diversity, which is required for high reliability HF communications.

This section finds that HF is viable for meter and decimeter level DGPS broadcast. However, the solutions obtained within this section are just one set of solutions based on a number of assumptions and worst case conditions. Changes may have to be made in order to accommodate special cases relative to available resources. Additionally, the HF alternative requires further study of the signal to be transmitted, and it requires investigation of which HF channels are available to USACE.

3.1.1 Meter Level DGPS

The accuracy requirement for the meter level DGPS application is 3-6 meters (1σ). This accuracy can be achieved by transmitting pseudorange corrections at 50 bps using the RTCM SC-104 recommended message format. The required bandwidth for such a communication link is around 100 Hz. The corrections are required over a circular area, with a radius of 1000 km, around the GPS reference receiver.

The primary application for the differential communication systems under study will be hydrographic surveying and dredging operations. Many of these surveying operations will take place aboard a small skiff (about 16 foot), which excludes the use of any large communication equipment. Fortunately, HF receiver equipment can be relatively small in size and very lightweight.

The meter level DGPS communication system could be set up in

a desired area as a permanent link. Because the transmitter(s) can be permanent, they may be large and require several days to assemble. This link would be capable of servicing unlimited users within the coverage area (1000 km radius circle, centered at the reference receiver station).

3.1.2 Decimeter Level DGPS

The requirements for the decimeter level DGPS applications are more stringent. The accuracy for the decimeter level DGPS system is 1 decimeter. This accuracy is very hard to accomplish in real-time, requiring a much greater correction update rate which in turn means a much higher data transmission rate and bandwidth. Transmission of the C/A-code pseudorange error corrections alone is not sufficient for such accuracy. However, broadcast of carrier phase information at the reference receiver can potentially yield decimeter accuracy.

The estimated data transmission rate is about 1000-2000 bps, requiring a link bandwidth of 1-4 kHz. This increase in bandwidth from 100 Hz, for the meter level DGPS system, increases the noise power at the receiver by 10 to 16 dB. Consequently, more transmitter power is required to account for the reduced SNR.

The corrections for the decimeter level DGPS system are only valid for an estimated range of 100 km from the reference receiver. Therefore, the coverage region for this type of decimeter level DGPS system would be a circular area with a radius of 100 km, centered at the reference receiver.

The transmitter for some decimeter level DGPS applications should be transportable, which limits size, weight and power. It should be relatively easy to set up within a few hours time.

3.2 HF Communication Properties

The HF spectrum lies between 3 and 30 MHz. Signals in this range reflect off of the earth's ionosphere, which allows long distance communications. There are, however, many variables that affect the reliability of the HF signals.

As illustrated in Figure 3.1, there are two modes of propagation for HF signals, groundwave and skywave. Groundwave propagation has been described in Section 2, and skywave propagation is the focus of this section. A skywave is refracted in the ionosphere to 'skip' back to earth for communication over great distances. Figure 3.2 shows how the radio wave ray paths

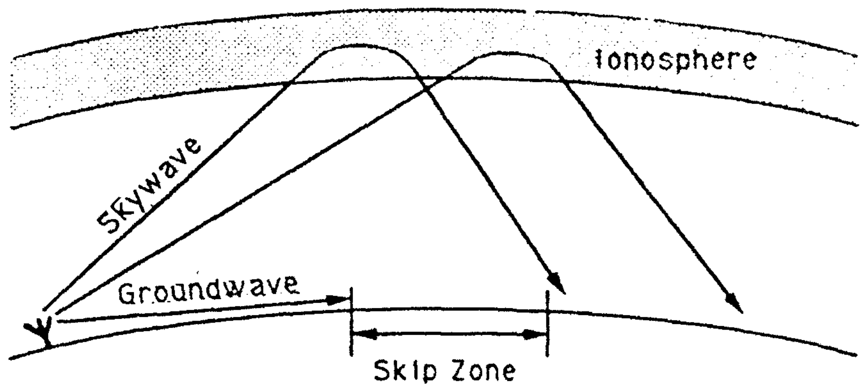

Figure 3.1: HF signal paths: groundwave and skywave

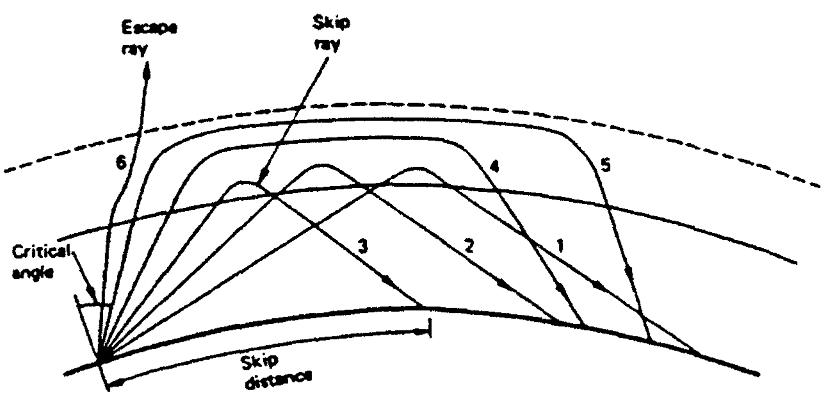

Figure 3.2: Ray paths as a function of angle of incidence for a fixed frequency.

are refracted and bent back towards earth [8]. Because the index of refraction in the ionosphere continuously decreases with increasing altitude, rays that have a higher incidence angle will carry farther through the ionosphere before their return to earth. Any rays above the critical angle will pass right through the ionosphere.

Skywave field strength and skip distance are dependent upon numerous factors. The biggest factor affecting refraction of the skywave is the electron concentration of the ionosphere, which is what controls the refractive index. The season, time of day, and number of sunspots all determine the electron concentration. HF signals propagate better with increased solar activity. Therefore, the radiolink reliability is better during the summer months. As for daily variations, the best transmission properties exist during the late afternoon hours. The electron concentration is also very high when there is a maximum number of sunspots. The number of sunspots varies over an 11 year cycle between a minimum of about 20 to a maximum of around 160.

HF systems are also limited by atmospheric noise and noise from man-made sources. Businesses located in cities produce the most noise perceivable to HF systems. However, even rural areas can produce disturbances that can affect the SNR at the receiver. For HF communication links with large bandwidths, noise can pose serious problems that can only be countered through the use of more transmitter power.

For the purpose of analyzing an HF communication link, worst case conditions must be simulated. Therefore, in designing typical HF communication links for meter level and decimeter level broadcasts, simulations were completed using 20 sunspots and noise levels typical of urban areas.

3.3 Analysis Techniques

This section describes the methods used to simulate and analyze HF communication links for use in both DGPS scenarios. A computer program was used to simulate the links and generate SNR contour plots. These plots were then used to determine if the link would be a reliable means of communication.

3.3.1 Simulation Software

A software package was used to compute field strengths and SNR contour plots, because of the numerous variables involved with analyzing HF communication links. This HF package was developed by NOSC to be used for U.S. government HF simulation projects. The program runs on an IBM compatible 80286 computer with an 80287 math coprocessor.

For both DGPS scenarios, the placement of the reference

receiver site was at 38°*N* Lat. and 90°*W* Long., which is near St Louis, MO. The HF system is required to provide circular coverage around the reference station. In the case of meter level DGPS, a circle of 1000 km radius should be covered; and in the case of decimeter level DGPS, a circle of 100 km radius should be covered.

The software allows you to place the HF transmitters and receivers anywhere on the globe. Other parameters are also specified for each station such as power, antenna type, antenna bearing (if directional), and if it is moving or stationary. Additional information must also be provided, such as link bandwidth, transmit antenna height, and the number of sunspots, for proper calculation of field strengths and SNRs. The software package has the ability to analyze the impact of atmospheric noise and different types of man-made noise.

After all appropriate data is entered into the station database (which can be saved and recalled), a single transmitter and receiver pair can be selected for analysis. The program can then generate groundwave propagation data, skywave field strength plots, or skywave SNR contour plots. From these different types of output data, one can tell if the link is effective or not and whether more power is needed or if a shorter or greater distance is needed (trying to work around the skip zone can sometimes be tricky).

In the simulations performed for this project, all receiver antenna types were omni-directional short whip antennas. The reason for this is the because of the nature of the applications; the receiver must be small, lightweight, and easy to use. In order to completely analyze if an HF transmitter or transmitters will sufficiently service the entire coverage area for each specific scenario, several receivers must be set up on the borders of the area and in the center. SNR link tests must then be performed for each receiver.

3.3.2 SNR Contour Plots

The NOSC HF simulation package can generate SNR contour plots for analyzing the communication links. These plots show what SNR is, for a particular transmitter/receiver pair, versus frequency and time of day. Using these plots, one can tell if a desired SNR can be achieved for reliable communication, using the selected power ratings, antenna types, and other parameters.

A typical SNR contour plot is shown in Figure 3.3. Frequency (in MHz) appears on the vertical axis, while time of day appears on the horizontal axis. Note, however, that the time of day is in Universal Time (UT) which is six hours ahead of

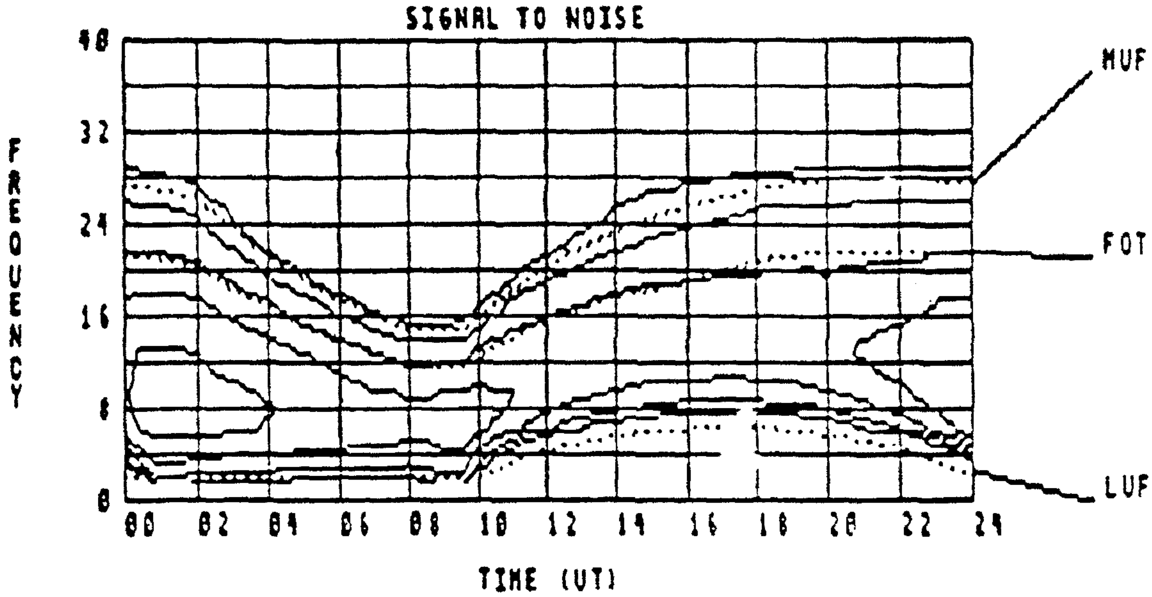

Figure 3.3: Typical SNR Contour Plot.

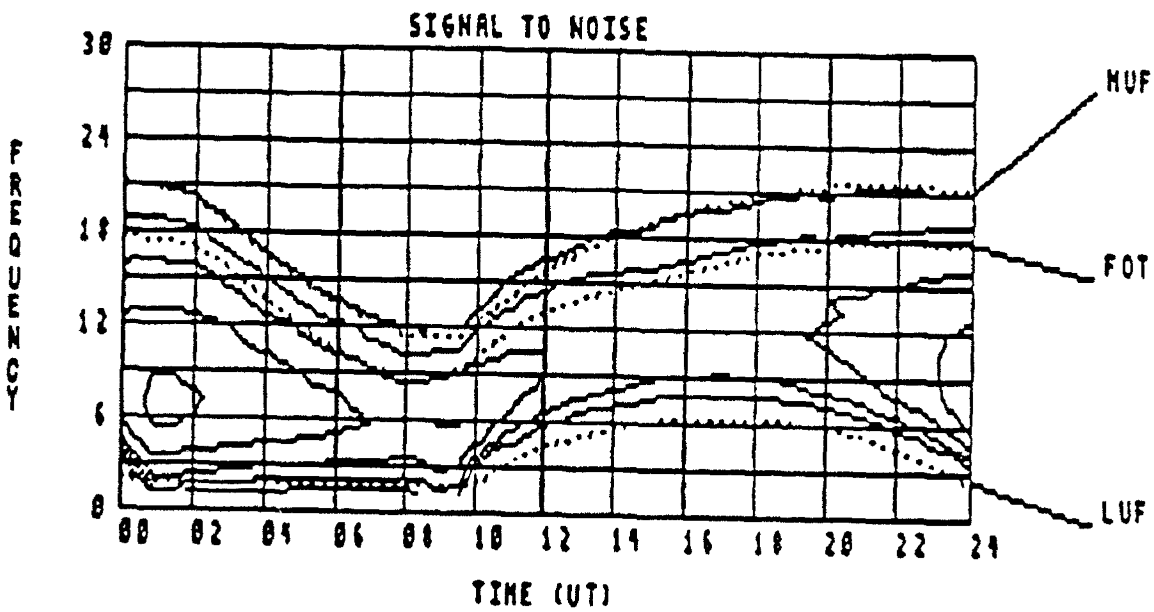

Figure 3.4: Example of bad connectivity SNR contour plot.

Central Standard Time (CST) in St Louis. Therefore, at time "06", it is actually 12:00 midnight.

Ignoring, for the moment, the labels at the far right (MUF, FOT, and LUF) and their respective dotted lines, the plot is actually very straight forward. The initial contour for this plot is -10 dB and the contour increment is +10 dB. This means that the uppermost and lowermost lines indicate the frequencies that will yield -10 dB SNR at a particular time of day (UT). All frequencies enclosed in these bounds at a particular time of day will have a SNR of at least -10 dB. The second set of lines (contour) directly inside of the first set of lines indicates the frequencies that can obtain a SNR of 0 dB. All frequencies contained within the third contour will have at least +10 dB SNR, the fourth contour represents +20 dB SNR, the fifth is +30 dB, etc.

In order to maintain reliable communication, a minimum SNR of +10 dB is required. Therefore, looking at the graph, it can be seen that for every time during the day, there are some frequencies that will yield a SNR of at least +10 dB (within the third contour). This type of connectivity of +10 dB is required across the entire day in order to make an HF communication link effective. An example of bad connectivity for an HF link is illustrated in Figure 3.4. Notice that the third contour is separated into two distinct parts and does not connect.

The labels at the right of the graph are the Maximum Usable Frequency (MUF), the Lowest Usable Frequency (LUF), and the FOT. The FOT is 85% of the MUF and is frequently assumed to be the optimum working frequency. The MUF is the highest frequency that can be refracted in the ionosphere at a certain time of day. The LUF is the lowest frequency that can be transmitted via skywave without being absorbed by the lower region of the ionosphere. Therefore, the operating frequency should never go out of these two bounds.

As shown in the figures, the best SNRs are achieved between 22:00 and 04:00 (UT) which are the late afternoon to evening hours (4:00 to 10:00 CST). As discussed earlier, the electron concentration in the ionosphere is greatest at that time of day.

3.4 Meter Level Broadcast Using HF Skywave

This section presents a feasible communication scheme using HF for the broadcast of DGPS corrections for meter level applications. A description of this communication scheme is provided, along with results from the NOSC simulation package. SNR plots are given for various test positions within the coverage area.

As previously mentioned, the coverage area for the meter

level application is a circular region of radius 1000 km that is centered at the reference receiver (St Louis in our analysis). The HF transmitter should not be placed at the center of the coverage region, because the skip zone between the groundwave and skywave signals gives rise to a large area that is uncovered by this system. To account for this, a multiple transmitter scheme has to be adopted.

Simulations indicate that a two transmitter network could accomplish the task if positioned in such a way that the skip zone of one transmitter would be covered by the second transmitter, and vice versa. The transmitter positions that we have chosen are shown in Figure 3.5. In order to use this communication scheme, the reference receiver would be placed at the center of the coverage area (St Louis) and the transmitters would be placed 500 km outside of the coverage area in opposite directions (1500 km away from reference receiver). The differential correction information would be sent to the transmitters via telephone lines using a modem.

The receiver locations indicated on Figure 3.5 (St Louis, N1000, S1000, E1000, and W1000) are the test positions used in the simulation analysis. If these locations can be covered, then the HF broadcast system shown in Figure 3.5 would provide adequate area coverage.

The simulations for this scenario were completed with variables for the worst-case. The variables used were:

Transmitter Height: 20 m

Sunspot Number: 20 (minimum)

Man Made Noise: Business

Bandwidth: 100 Hz

Transmitter Antenna Type: 5 Element Yagi

Receiver Antenna Type: Short Whip

Transmitter Power: 1000 W

Since HF waves propagate differently in different directions because of the earth's magnetic field, several tests for the links had to be conducted. The results of these tests have proven that this configuration of transmitters can be set up in any position, 1500 km from the center and in exact opposite directions. The least reliable link set would be with the two transmitters set up in a North-South configuration. The SNR

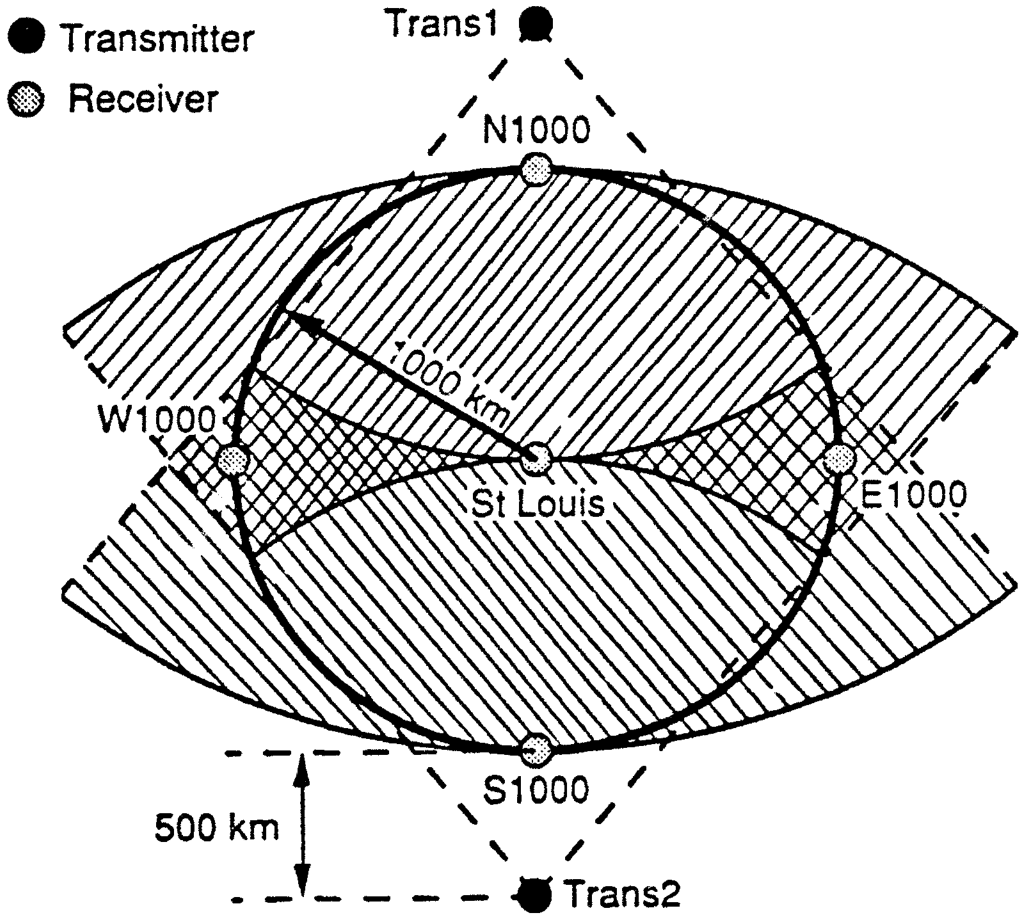

Figure 3.5: Scenario map for meter level DGPS applications.

contour plots for each individual test link are given in Figures 3.6 through 3.13. These plots are for the North-South configuration, where TRANS1 is north of the coverage region and TRANS2 is south.

As can be seen in these SNR plots, all have good +10 dB connectivity across the entire day. These simulations were completed using 5 element Yagi transmitter antennas. Moreover, additional simulations indicate that the Yagi is very well suited for this application.

3.5 Decimeter Level DGPS Using HF Skywave

The coverage area for the second scenario, decimeter level DGPS, is a circular region of radius 100 km centered at the reference receiver. Once again, this coverage area cannot be served with a single transmitter at the center of the coverage region. The groundwave can not be reliably transmitted more than about 20 km, and the skywave would not be seen until about 1000 km away. For these reasons, a single transmitter is placed 2,350 km away from the center of the coverage region (shown in Figure 3.14).

The great distance of the transmitter from the coverage region could pose some problems. The DGPS correction information would again have to be sent to the transmitter via phone lines. For link analysis purposes, simulations must be completed for each of the five receivers (St Louis, N100, S100, E100, and W100) from the transmitter.

The simulations for the decimeter level DGPS scenario were completed with the following variables:

Transmitter Height: 2 m

Sunspot Number: 100 (average), 20 (minimum)

Man Made Noise: Business

Bandwidth: 4 KHz, 1 KHz

Transmitter Antenna Type: Horizontal LPA

Receiver Antenna Type: Short Whip

Transmitter Power: 325 W

Since this scenario was originally specified to be a portable station that could be set up in several hours, many of the variables used in the simulations have been changed from the meter level broadcasts. The transmitter height, for instance, is

Trans1 ⟹ St Louis:

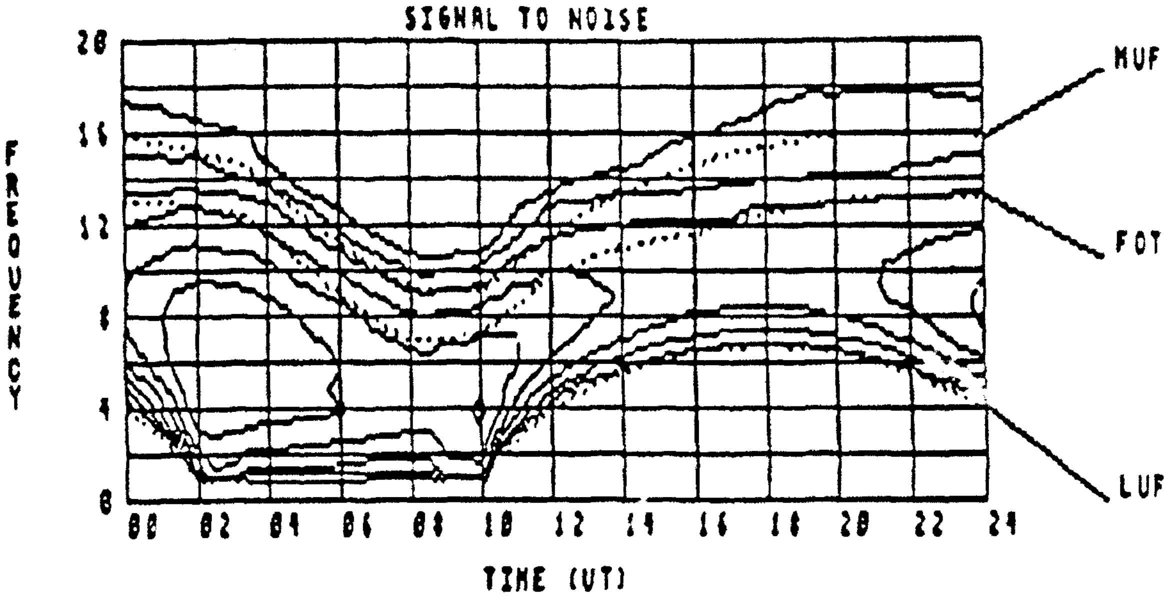

Figure 3.6: SNR contour plot for Trans1 to St Louis link.

Trans1 ⟹ W1000:

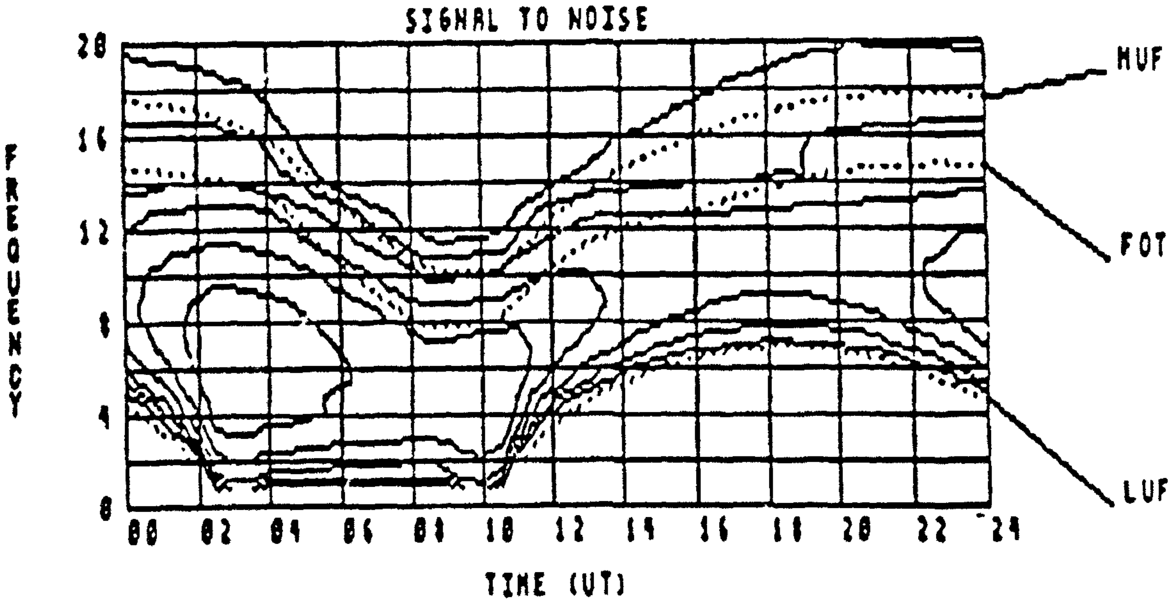

Figure 3.7: SNR contour plot for Trans1 to W1000 link.

Trans1 ⟹ S1000:

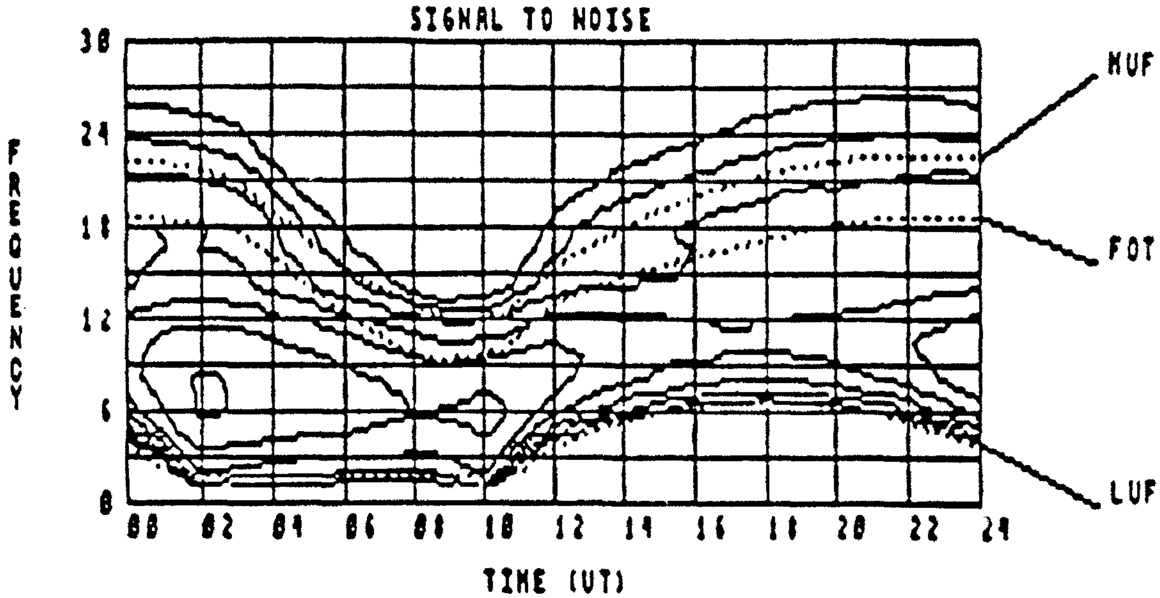

Figure 3.8: SNR contour plot for Trans1 to S1000 link.

Trans1 ⟹ E1000:

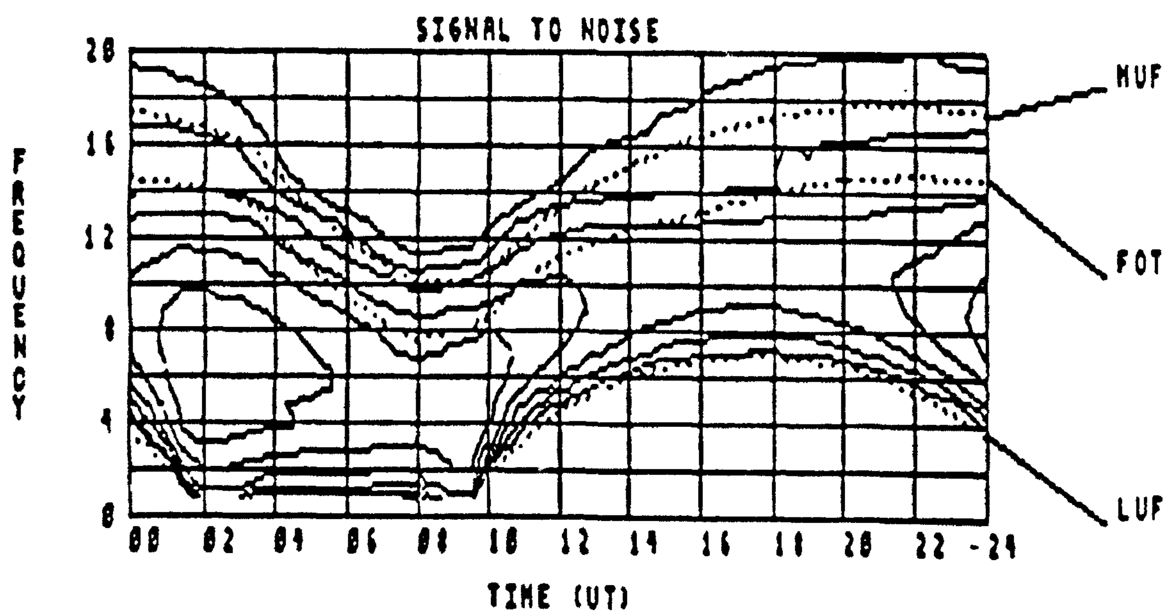

Figure 3.9: SNR contour plot for Trans1 to E1000 link.

Trans2 ⟹ St Louis:

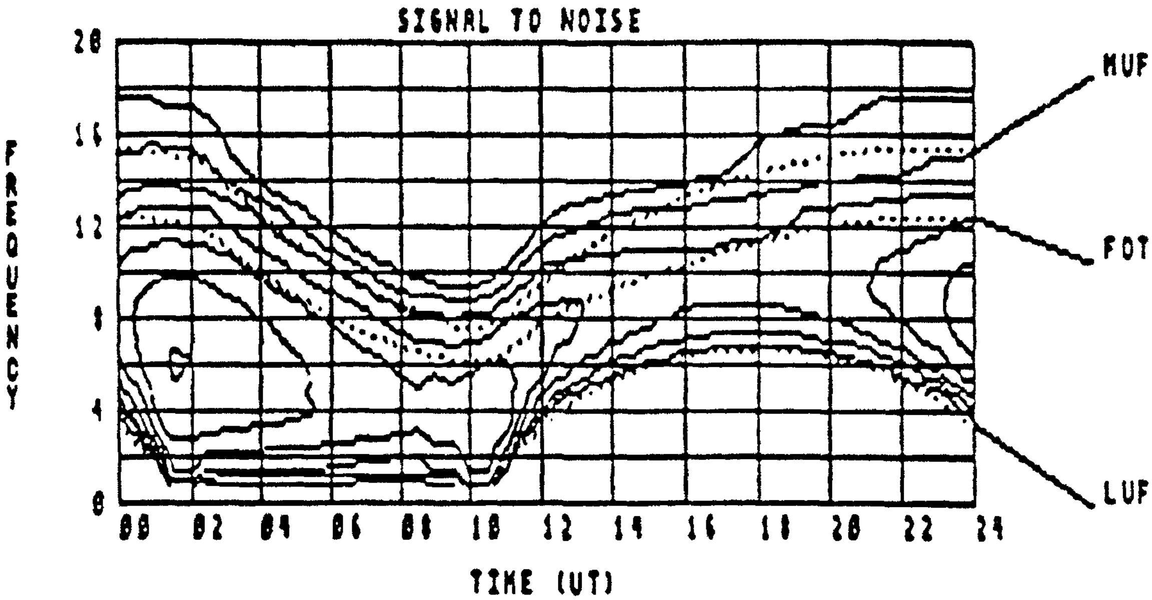

Figure 3.10: SNR contour plot for Trans2 to St Louis link.

Trans2 ⟹ W1000:

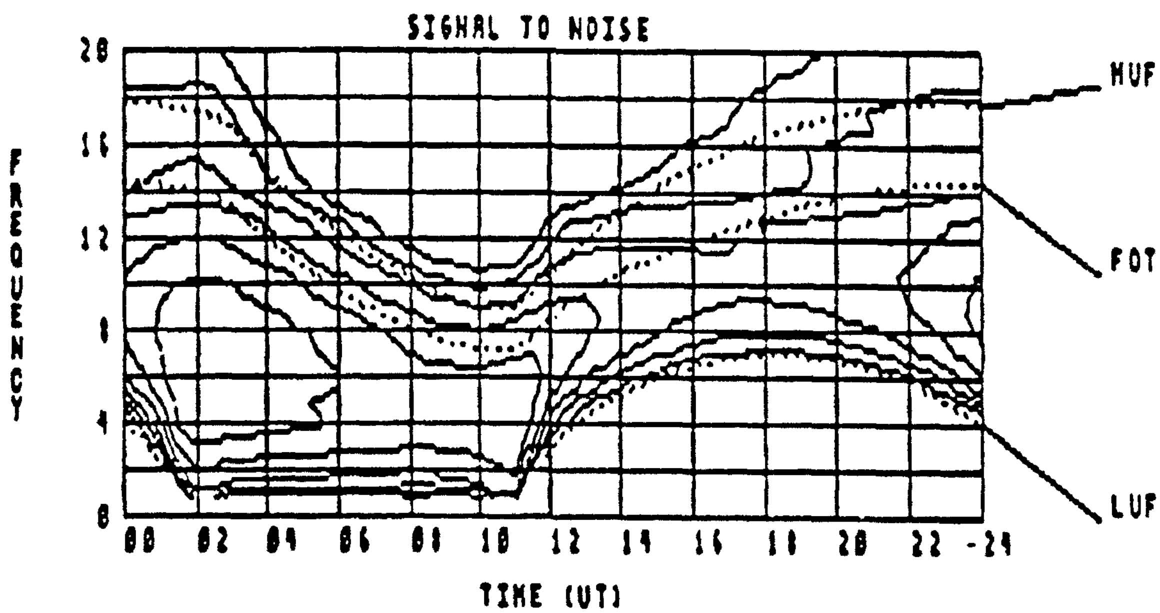

Figure 3.11: SNR contour plot for Trans2 to W1000 link.

Trans2 ⟹ N1000:

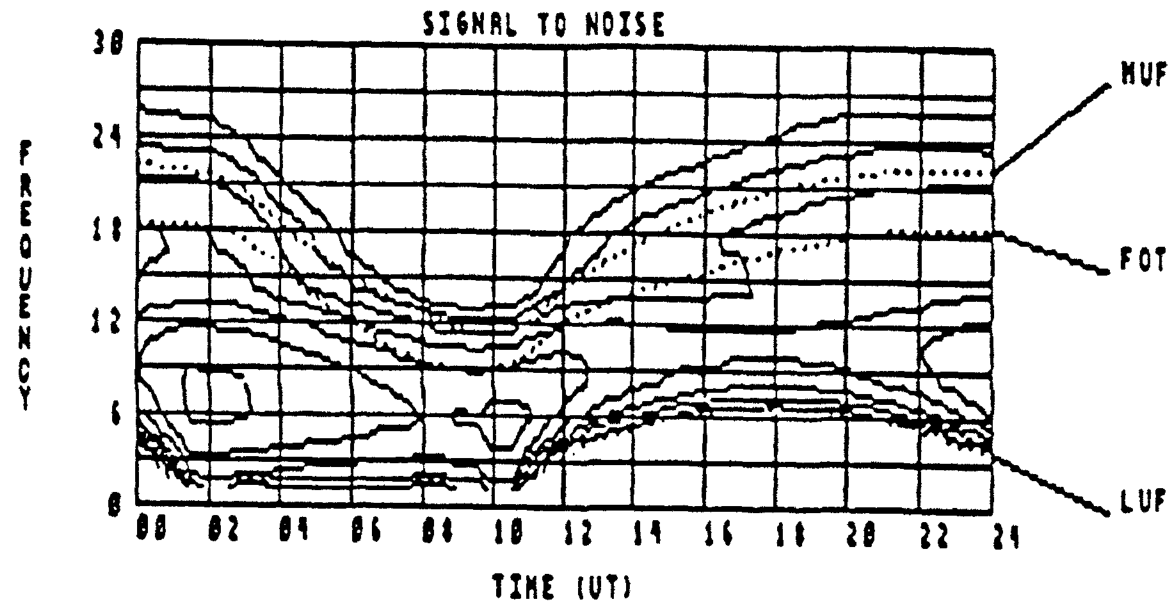

Figure 3.12: SNR contour plot for Trans2 to N1000 link.

Trans2 ⟹ E1000:

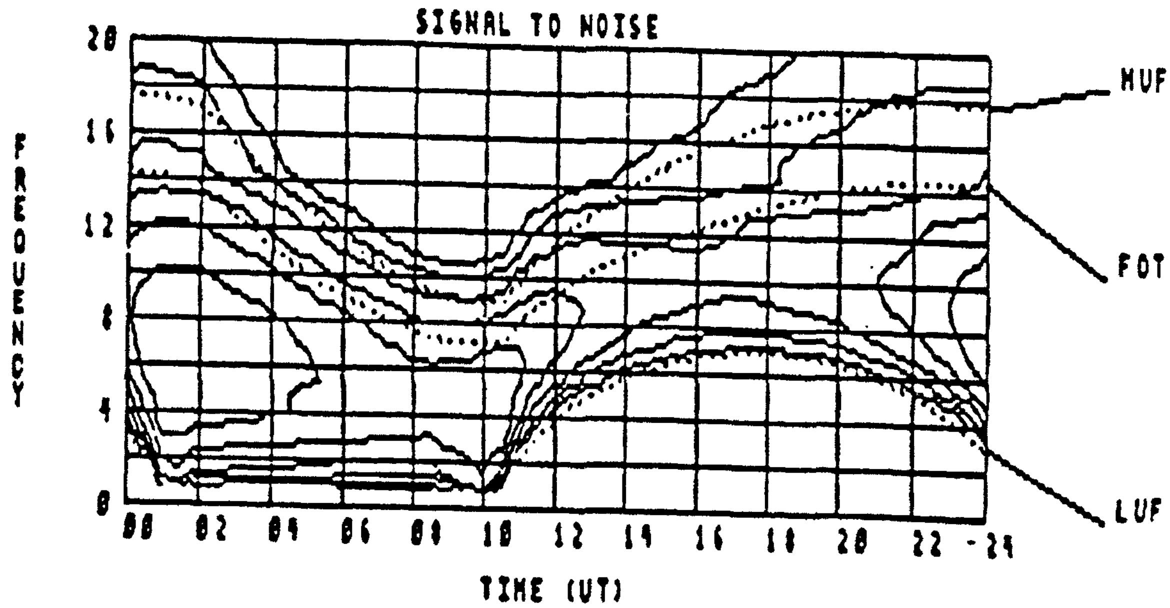

Figure 3.13: SNR contour plot for Trans2 to E1000 link.

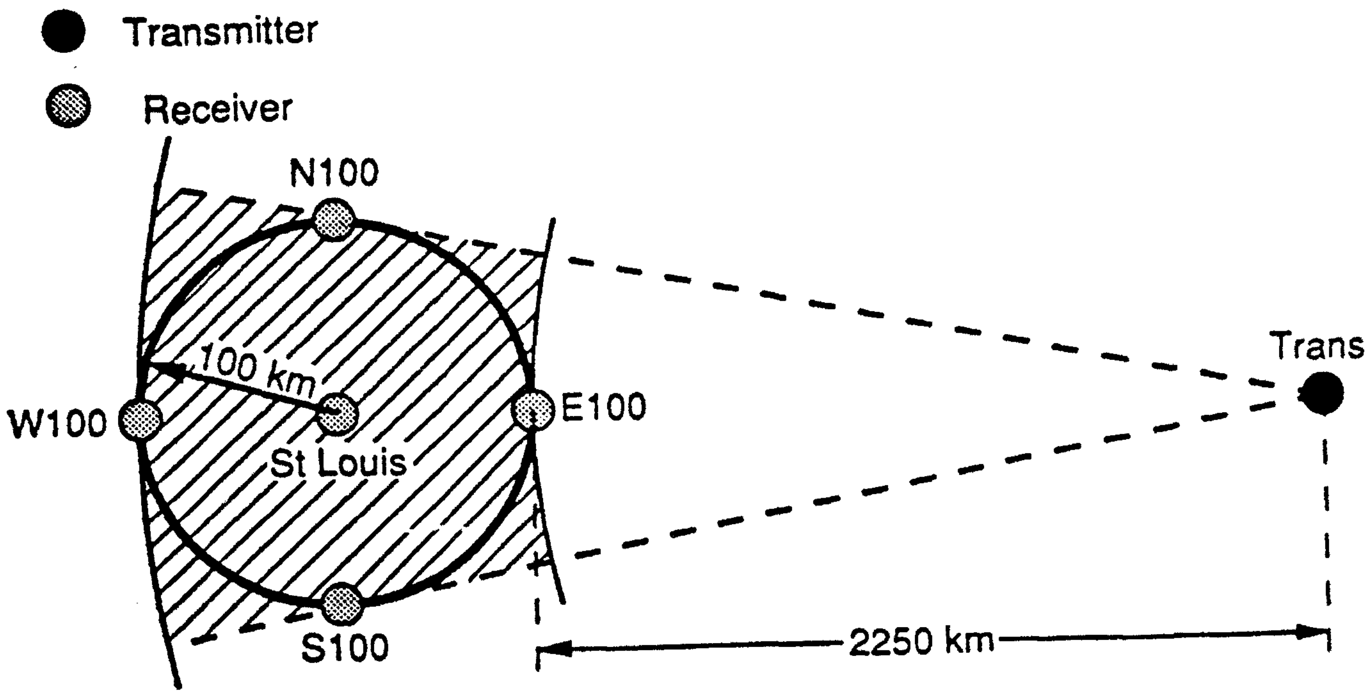

Figure 3.14: Scenario map for decimeter level DGPS applications.

much smaller because it is a portable transmitting station. For the same reason, less transmitter power becomes necessary for practical transportation. The bandwidth, on the other hand, is substantially higher than that for meter level DGPS. As previously stated, a bandwidth of 1-4 kHz is necessary to achieve decimeter accuracy.

The first set of tests were completed for a bandwidth of 4 kHz and 100 sunspots. Figure 3.15 through Figure 3.19 show that a transmitter power of 325 W is sufficient to ensure link connectivity of +10 dB or better throughout the day.

These tests, however, were completed with 100 sunspots which is average solar activity. Further tests must be completed to see what effect a solar minimum might have on the link reliability (a sunspot number of 20). Figure 3.20 is the SNR contour plot for the Trans to St Louis link with only 20 sunspots while maintaining a transmitter power of 325 W. The loss of +10 dB connectivity is obvious from the plot.

The power needed for reliable operation with only 20 sunspots was then determined to be 3000 W. However, if the required bandwidth is constrained to be only 1 KHz instead of 4 KHz, then the required power is only 750 Watts, even with a sunspot number of 20. Since the format for decimeter corrections has not been defined at this time, the exact bandwidth required is not known. However, minimizing techniques could be employed to reduce the required data rate and, consequently, the necessary bandwidth which would be very important for the HF broadcast of decimeter level corrections.

One final consideration for this HF communication scenario is the placement of the transmitter antenna. A distance of 2,350 km from the reference receiver was used, but as previously stated, caution must be taken when developing HF links since the waves travel differently, dependent on direction, through the earth's magnetic field. This fact influences our analysis as described below.

It has been determined that 2,350 km is the optimum distance for a transmitter that is located to the east or west of the reference receiver. The initial plots shown above are all from a transmitter located east of the reference receiver, however, the results from both directions are similar. They both require 3,000 W for 20 sunspots and a bandwidth of 4 kHz, and 750 W for 1 kHz.

A transmitter placed to the north or south of the reference receiver, however, would have to be placed 2,500 km from the reference station. In addition to this, a transmitter power of 10,000 W is needed for a reliable link with a sunspot number of

Trans ⟹ St Louis:

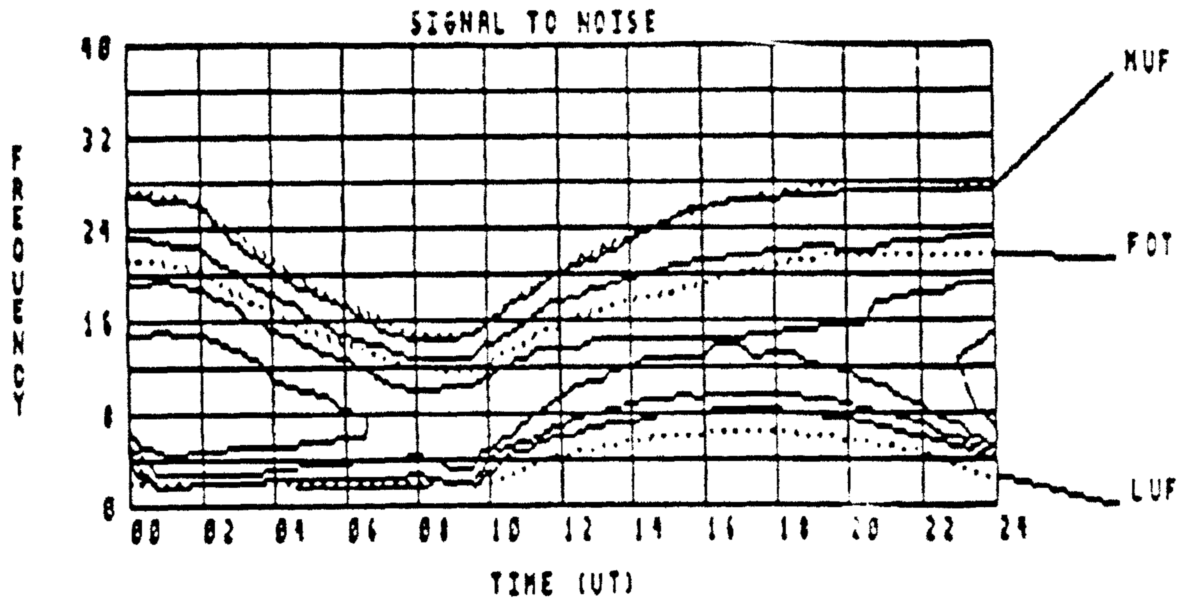

Figure 3.15: SNR contour plot for Trans to St Louis link.

Trans ⟹ N100 :

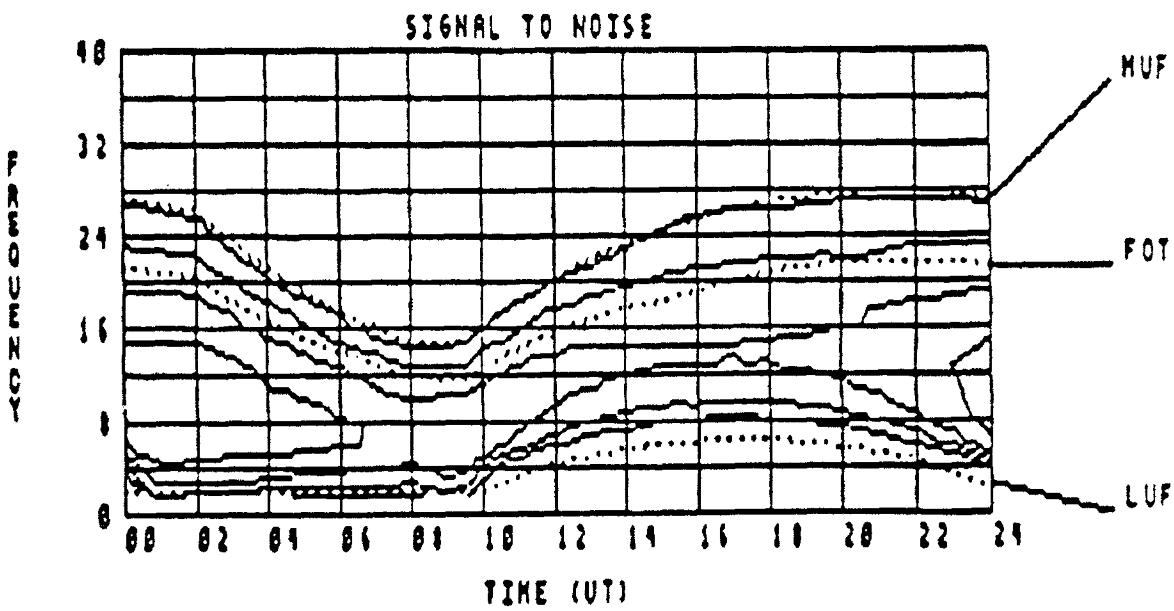

Figure 3.16: SNR contour plot for Trans to N100 link.

Trans ⟹ E100 :

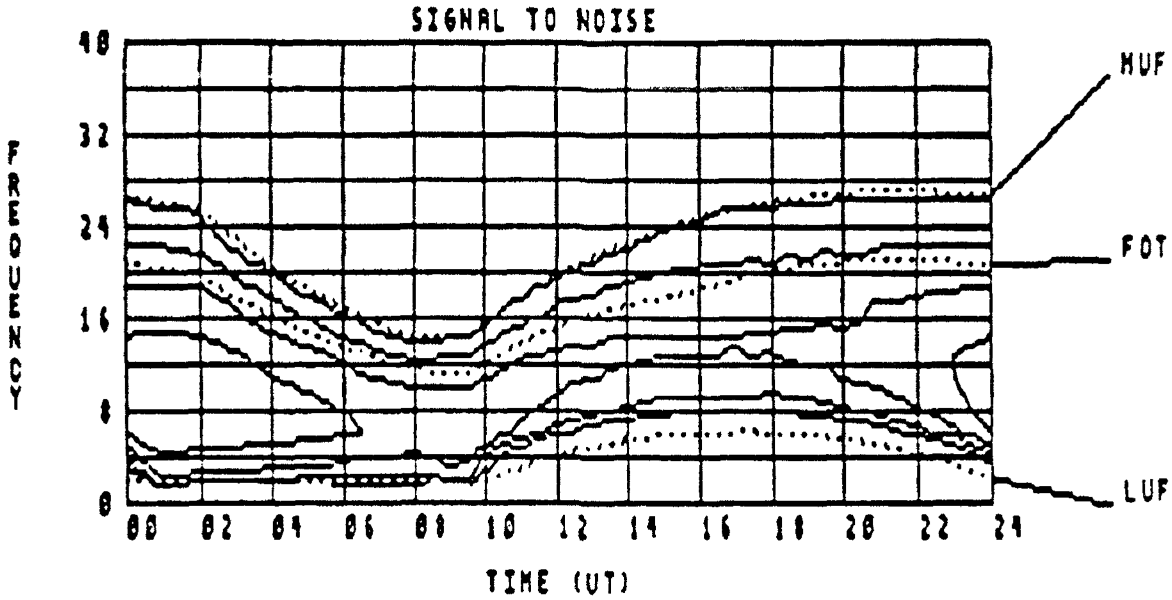

Figure 3.17: SNR contour plot for Trans to E100 link.

Trans ⟹ S100 :

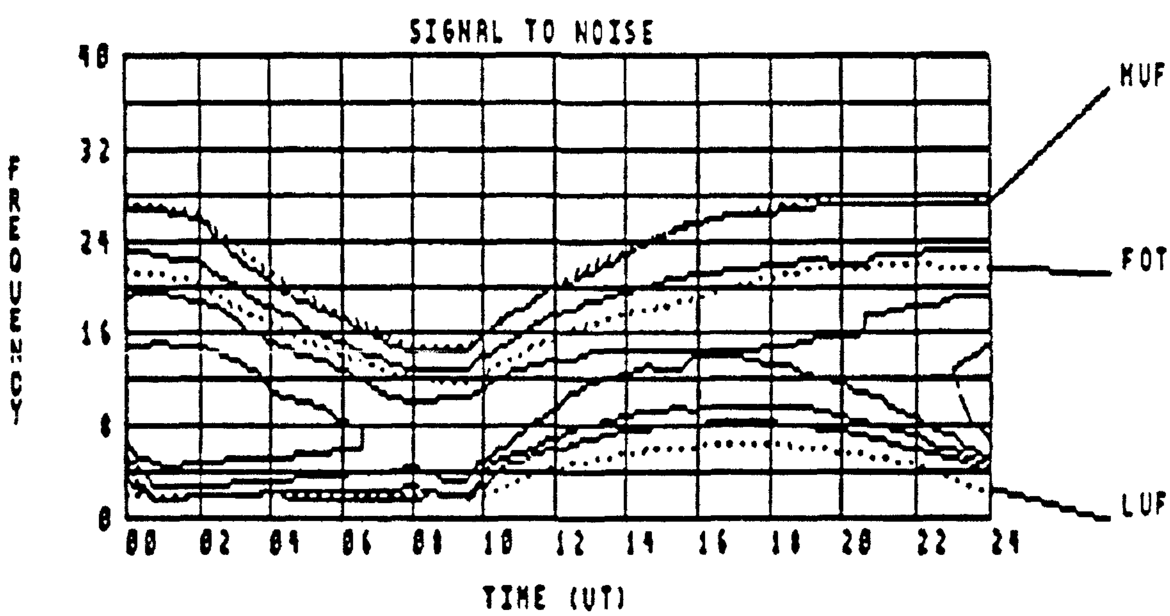

Figure 3.18: SNR contour plot for Trans to S100 link.

Trans ⟹ W100 :

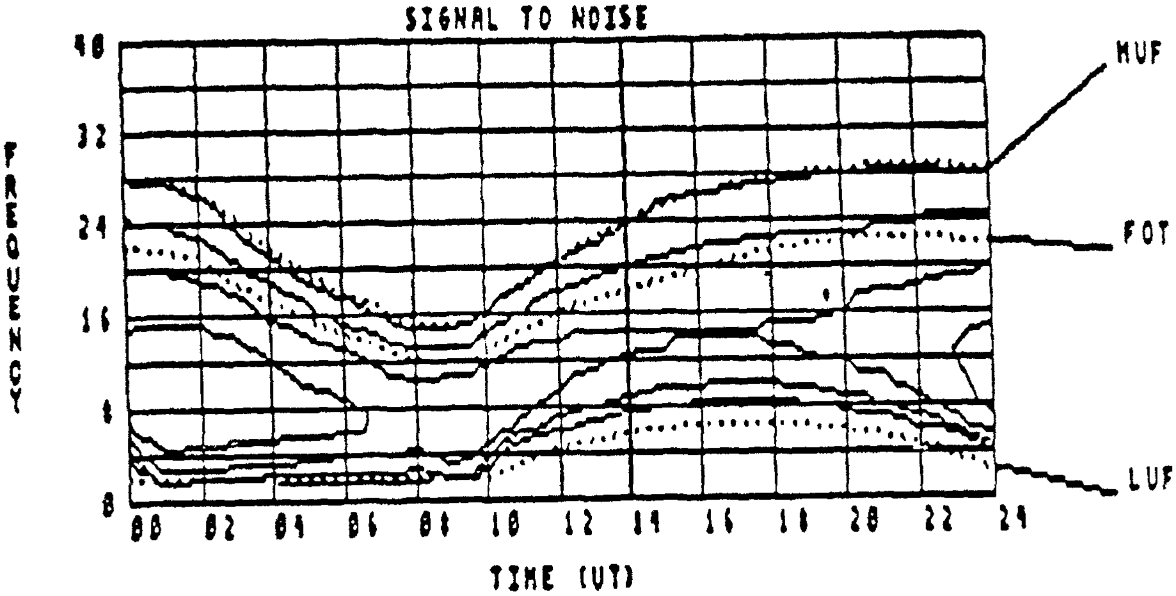

Figure 3.19: SNR contour plot for Trans to W100 link.

Trans ⟹ St Louis: (Sun Spot Number: 20(min))

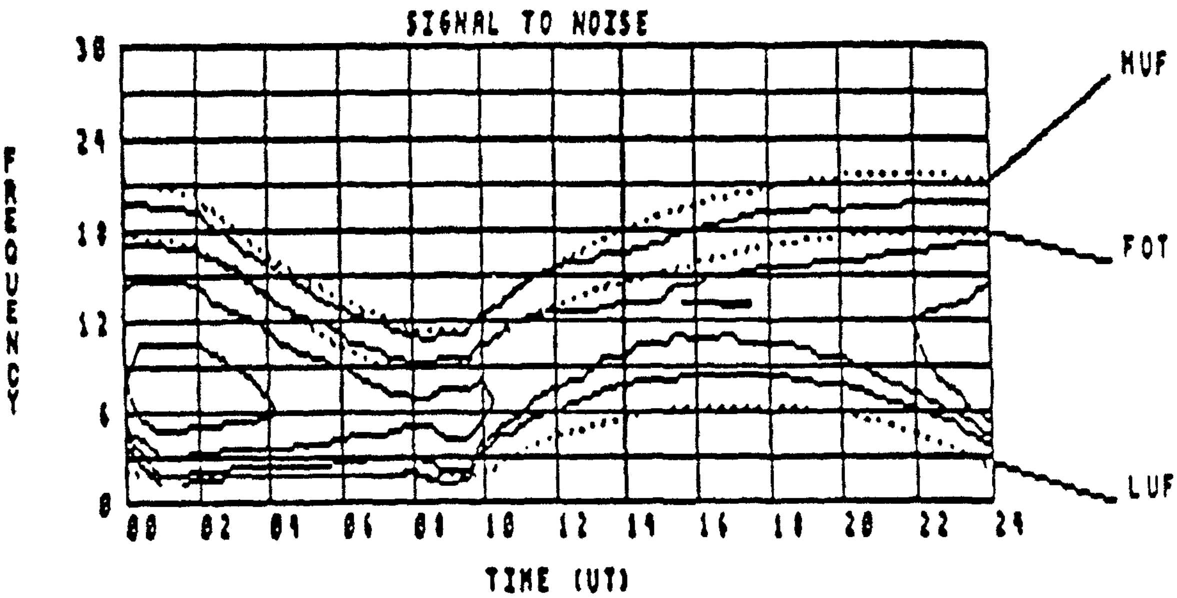

Figure 3.20: SNR plot for Trans to St Louis, 20 sunspots, 325 W.

20 and a 4 KHz bandwith. Hence, east and west configurations are strongly preferred.

3.6 Frequency Diversity

The NOSC HF software produces the SNR contour plots based on an 85% confidence level. Indeed, signal fading causes the SNR to be weaker than indicated in the plots 15% of the time. In order to provide a communication link that is highly reliable, the use of frequency diversity is required. A frequency diversity system would broadcast on 3 or 4 frequencies simultaneously and is shown in Figure 3.21.

Two types of receiver could be used. A scanning receiver would scan the 4 frequencies until it found a channel with adequate performance. It would dwell on that frequency until performance became inadequate, then it would scan for a new channel. Alternatively, the receiving system could include 4 separate receivers and receive all 4 channels all the time. The 4 receivers would be followed by a combiner which would combine the data from the separate channels.

Each transmitter may cost from $20,000 to $30,000. Each receiver costs around 2000 and a new combiner unit requires development. In addition, USACE would have to develop an HF signalling scheme based on available channels and tests.

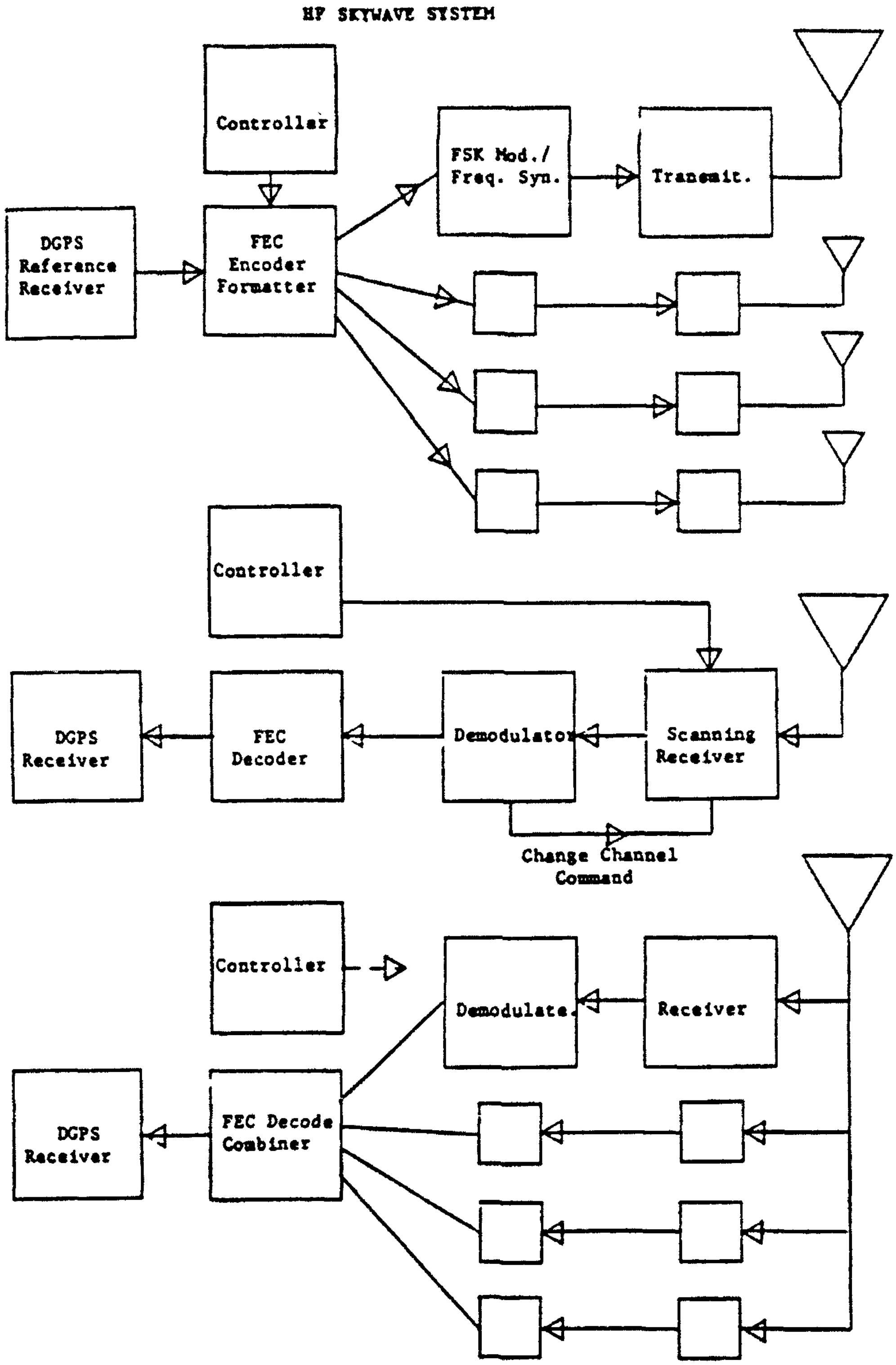

Figure 3.21: An HF Broadcast System Which Uses 4 Frequency Diversity.

Section 4

VHF and UHF Networks

4.1 General

Radios which operate in the very high frequency (VHF, 30 to 300 MHz) and ultra high frequency (UHF, 300 to 3000 MHz) ranges can reliably communicate data over short distances. Very roughly, a VHF or UHF radio can communicate to the radio horizon, which is equal to

$$D(km)=4.12(\sqrt{h_1(m)}+\sqrt{h_2(m)})$$

where $h_1(m)$ and $h_2(m)$ are the heights of the receiving and transmitting antennas. Over water, "ducting" phenomena make reliable signal reception over longer ranges possible. For example, a 4 Watt transmitter on the coast at water level can reliably be received by a ship 40 miles from the coast. However, overland propagation is limited by line of sight, and overland range prediction requires a detailed path profile. Propagation along a coast also requires an analysis of the path profile to determine whether any obstructions exist.

VHF and UHF radio channels are afflicted by a number of generic problems. First, the VHF or UHF signal can be shadowed by valleys, hills, buildings, and even trees. Second, multipath fading can impair quality particularly if the mobile receiver is at larger ranges. In general, if area coverage beyond line of sight is required, then networks of repeaters are required. In fact, the Wilmington District office already has a wide area voice network based on line of sight radio. If modems are used, then this network may be well suited for DGPS broadcast. However, data transmission is more fragile than voice, and tests will be required to determine whether or not additional repeaters are required.

The next section describes a typical VHF/UHF radio system. The remaining sections in this section consider the following in-place VHF/UHF data-broadcast systems:

1. TV Vertical Blanking Interval (VBI)

2. Cellular Radio

3. Special Mobile Radio Systems (SMRS)

4. FM subcarrier

4.2 Typical VHF/UHF Digital Radio

A typical VHF/UHF digital radio is shown in Figure 4.1, with the transmitter on the top and the receiver on the bottom. The DGPS reference receiver provides the data to an error detection algorithm, which adds parity bits to the data stream. The encoded data then modulates the carrier and the resulting signal is broadcast by the VHF/UHF transmitter.

The receiver is usually integrated with the demodulator, and this pair returns a binary data stream to the parity check algorithm along with a "carrier detect (CD)" signal. The parity check algorithm then checks for transmission errors, and if none have occurred, the data is passed to the DGPS receiver.

Two types of VHF/UHF repeater are shown in Figure 4.2. In the top portion of the figure, the received signal is routed to the receiver by a combiner. The receiver simply connects its intermediate frequency output to an IF input on the transmitter. The transmitter then shifts the frequency of the signal. In other words, the channel is full duplex; the repeater receives on one frequency and simultaneously transmits on another frequency.

The repeater shown in the bottom portion of Figure 4.2 can be used in half or full duplex mode, because it demodulates the DGPS signal all the way down to baseband. The receiver output is connected to a demodulator, which outputs a binary data stream to the decoder. The decoder applies the parity algorithm, and if the data is error free, then the data is re-encoded, modulated and transmitted. If the channel is half duplex, then the receiver uses the duplexor, and the baseband data is stored until the transmitter sends. The receiver is turned off while the transmitter sends, and the transmitter need not shift frequency. If the channel is full duplex, then the send and receive frequencies are different, and a combiner is used at the antenna.

Full duplex operation is recommended for DGPS, for two reasons. First, half duplex operation increases the data delay. Second, if the repeater "hangs up" in the transmit mode, then the repeater cannot receive commands to turn off the transmitter.

Geotel Inc. of New York manufactures all the elements shown in Figures 4.1 and 4.2, and provides the following data. A digital VHF/UHF transmitter which integrates the modulator and transmitter shown in Figures 4.1 and 4.2 costs approximately $650 in small quantities [9]. It uses FSK modulation and can upconvert the modulated signal to VHF or UHF. Physically, it is 4" by 5" by 1". The corresponding digital data receiver, which integrates the demodulator and receiver blocks shown in Figures 4.1 and 4.2, costs approximately $700. It is also around 4" by

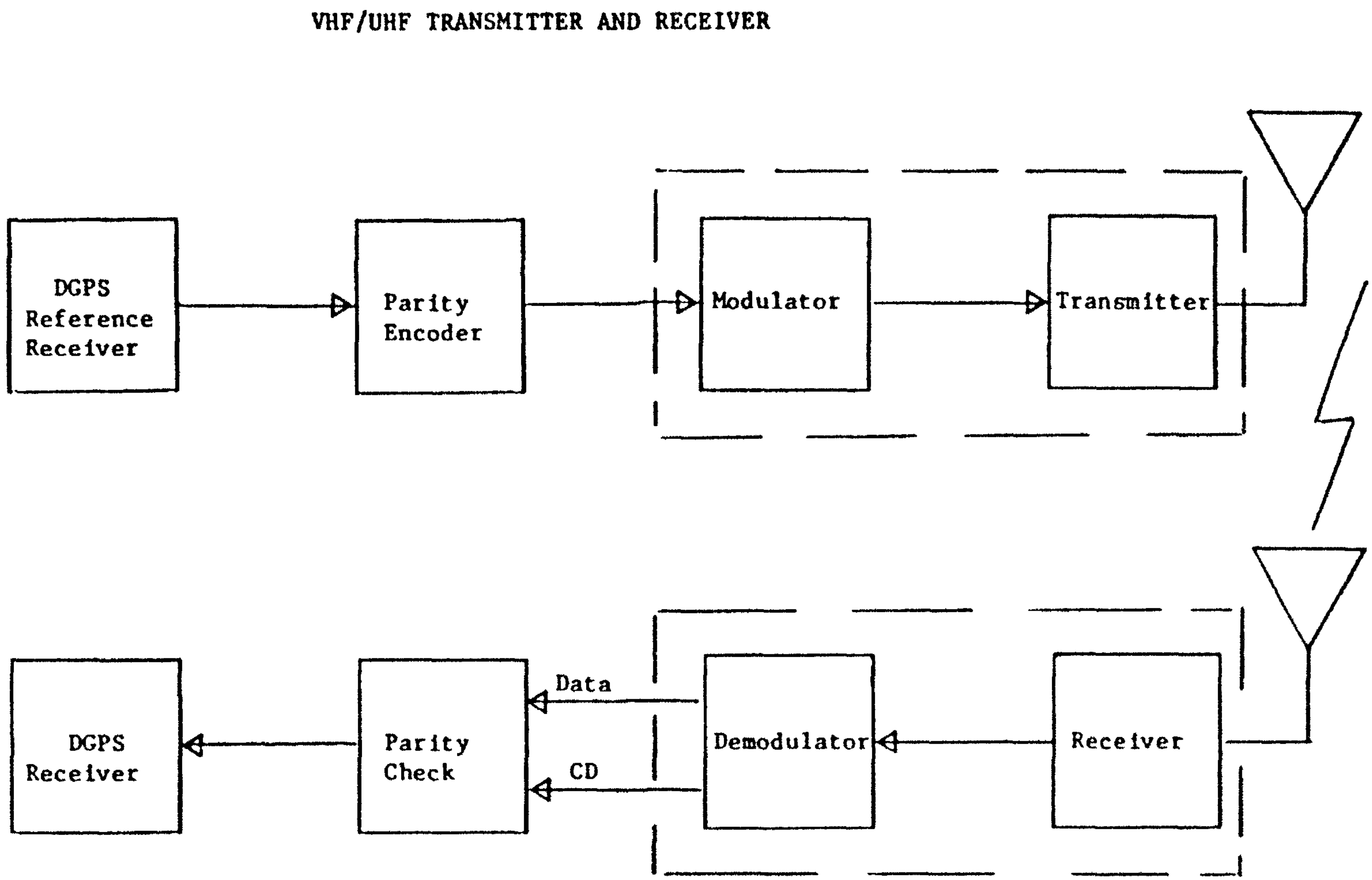

Figure 4.1: VHF/UHF Transmitter and Receiver.

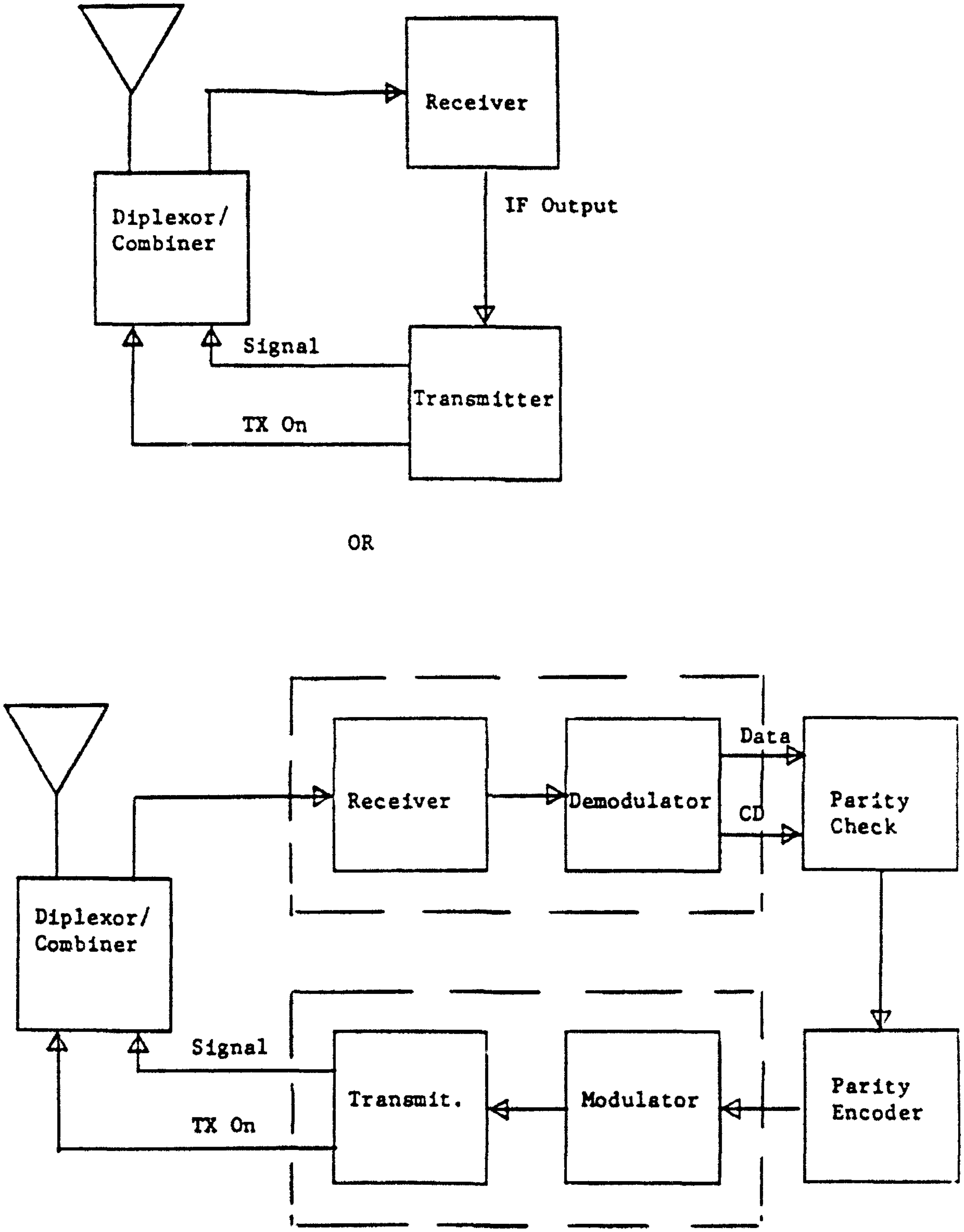

Figure 4.2: VHF/UHF Repeater.

5" by 1". Each of the parity blocks cost around $100 and can be provided on a single printed circuit board. A small non-recurring engineering cost would be added to the first of these PC boards.

Antenna diversity has been used to combat multipath interference in VHF/UHF radio. For example, Sony manufactured a two antenna system for FM radio in cars. The radio switched to the antenna which gave the strongest signal. Additionally, Geotel successfully produced a multiple antenna system for use by General Motors in factory floor applications of VHF/UHF radio.

4.3 Television Vertical Blanking Interval

A television picture has 525 horizontal lines, and the first 21 of these are VBI. They blank the screen during retrace and they can carry information. For example, they have been used to broadcast TV test signals, and Teletext (in Europe). Line 19 is used for color control to certain televisions, and line 21 is used to provide closed captions to the hearing impaired.

PBS uses the VBI to provide a national data broadcast system. This system called National Datacast and is shown in Figure 4.3. It can broadcast 9600 bps per vertical line, and there are 6 to 10 lines per station. This service is well suited for the broadcast of DGPS data in a number of respects. First, PBS can deliver data to all of their affiliates via a satellite broadcast system. Second, PBS covers 97% of TV households over the air and has federal and state mandates to cover unserved areas. Consequently, their nationwide coverage, which is shown in Figure 4.4 is quite good. Finally, the National Datacast system was designed for small data latency: 2 seconds from bit arrival at PBS to user decoder output.

The cost of nationwide broadcast using PBS is $30,000 per month for 1200 bps or less and $33,000 per month for 2400 bps [10]. The remote equipment is small and costs $300. Additionally, National Datacast can be used to broadcast from individual PBS TV stations, and the cost is significantly lower than a national broadcast.

PBS Datacast is an attractive alternative for nationwide broadcast of DGPS data. If such a service becomes desired, then USACE must investigate the performance of this system to mobile users. Indeed, PBS Datacast to mobile users has been investigated once or twice, but is not used regularly. Additionally, PBS TV stations only broadcast 18 hours a day, and this may be an important limitation.

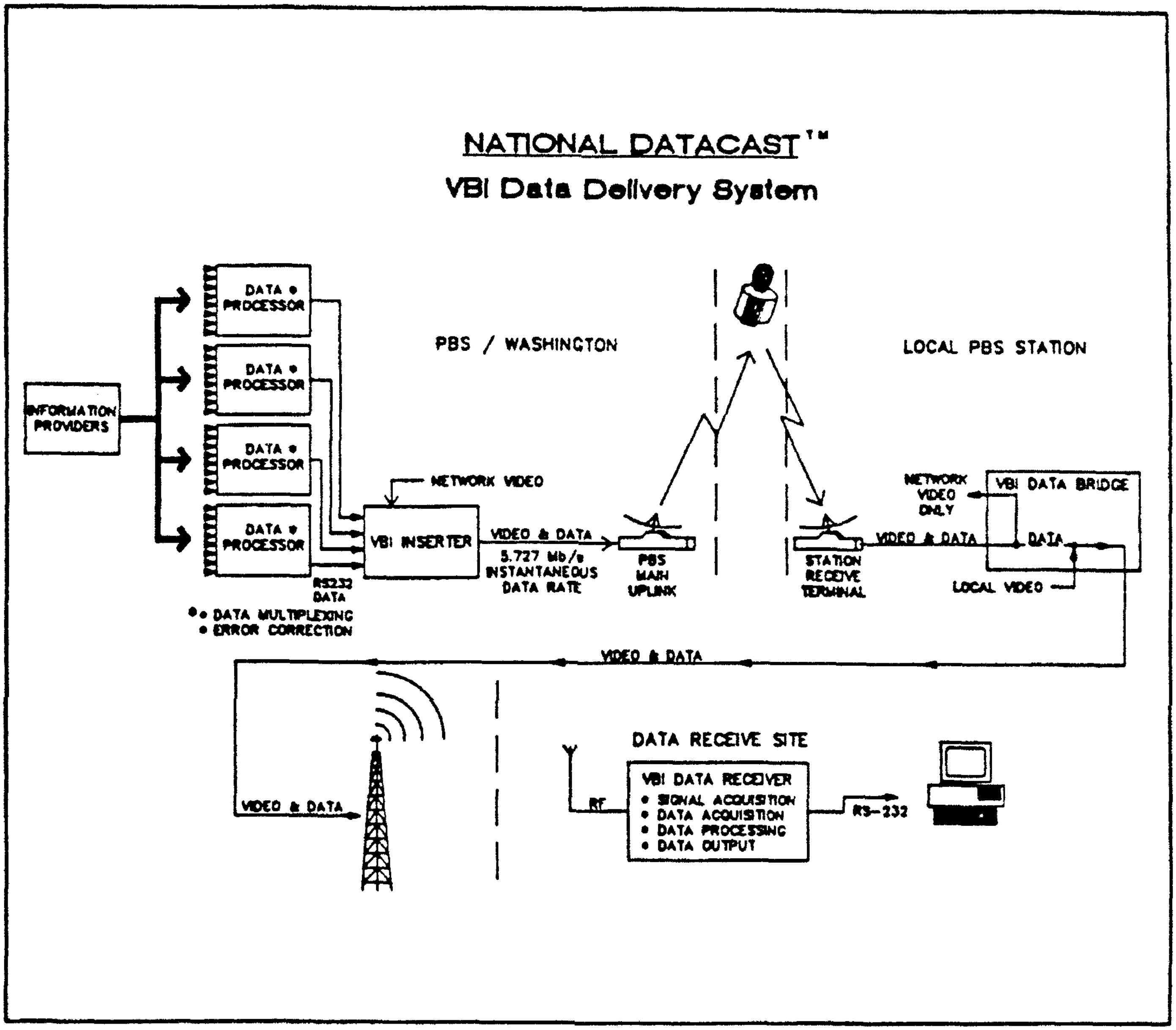

Figure 4.3: The Public Broadcast System's National Datacast System.

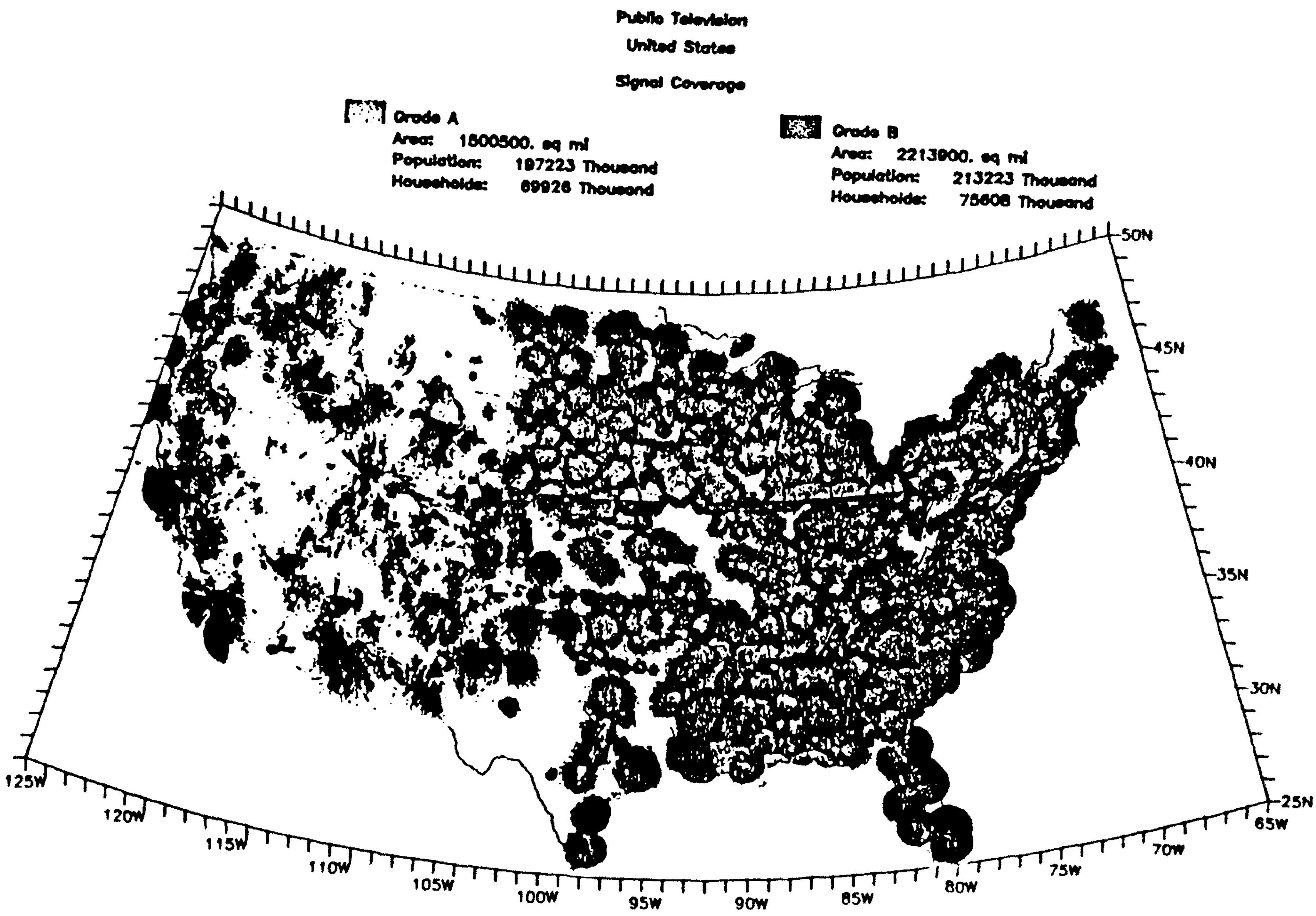

Figure 4.4: Nationwide Coverage of Public Broadcast System Television.

4.4 Cellular Radio

Cellular radio is spreading across the United States to provide telephone and data service to mobile users. It divides a given coverage area into small cells (hence its name), and each cell is served by a single transmitter. Additionally, each cell is given a fixed set of frequency pairs (one for receive and one transmission), and adjacent cells are given different frequency sets. However, cells which are not immediately adjacent can reuse the original set of frequencies, and the overall system achieves efficient use of the spectrum.

A mobile crossing a cell boundary is "handed over" to the transmitter in the middle of the next cell. This handover is automatically handled and coordinated by a network of fixed receivers, which judge when such a handover should take place. Such a handover does not disrupt voice use, but can present a problem for data transmission, which is more fragile. Fortunately, an appropriate coding scheme and hardware called the Bridge and Span have been developed by Novatel Inc. If any user crosses into a cell where all channels are occupied, then the call is terminated. However, this phenomena would not be too troublesome for USACE applications, which involve slowly moving mobiles.

Otherwise, cellular radio suffers the same drawbacks as all VHF and UHF systems: signal blockage in cities and rough terrain and multipath fading particularly at longer distances.

Cost data for cellular telephone was supplied by Motorola in Arlington Heights, Illinois, because this group provides nationwide cellular telephone service. The basic monthly fee is $15 to $50 per month per mobile. The cost of off peak air time is $0.10 to $0.12 per minute depending on location in CONUS. The cost of peak air time can be as high as $0.50 per minute (New York City and Los Angeles).

The cost of a permanent circuit for decimeter or meter level DGPS would be reduced slightly, because of the availability of bulk rates, which average around $0.20 per minute. The cost for a 2400 bps link for 22 eight hour days would be around $2112 per month per <u>mobile</u>. If 24 hour a day service is required, then the costs would be roughly three time as great. The cost of a phone circuit from the reference station to the local cell must also be added. If this call is long distance, then the additional cost would be around $1000 per month.

To use cellular telephone, TEC would have to develop:

- the interface from the reference receiver to the modem for the phone line

- the interface from the mobile phone to the DGPS receiver

However, the main limitation to the user of cellular telephone is the very limited coverage which is now available. Figure 4.5 is a coverage map for cellular in the U.S. and Canada. Note that coverage is strong in Urban areas and the Gulf of Mexico. However, areas without appreciable cellular markets are completely uncovered. Certainly cellular coverage will increase, but only when market conditions are suitable. Cellular phone may provide DGPS communications to USACE, but only in those areas which are well covered. In these situations, only modest development will be required and the operating cost will be relatively low.

4.5 Special Mobile Radio Systems (SMRS)

SMRS are terrestrial radio networks which operate in the 800 MHz band for special commercial applications. Two SMRS are briefly described here:

- Advanced Radio Data Information Service (ARDIS)

- Motorola Data Plus

ARDIS is a SMRS designed to support field service of "high tech" equipment. It connects the field personnel to their home computer for troubleshooting advice, diagnostics and parts information. It is based on a network of base stations which Motorola originally built for IBM, and has significant coverage in 400+ metropolitan areas (including Hawaii and the Virgin Islands). It is designed to provide in-building coverage; 12 base stations are used for Chicago.

The cost to use ARDIS is $0.08/packet, where each packet contains 240 characters and each character is 8 bits. Consequently, the cost for meter level DGPS service for 8 hours a day 22 days a month would be approximately $1,320/month. The cost for decimeter level DGPS would be approximately $52,800/month.

ARDIS is designed for interactive use between the service technician and his home computer. However, it is a packet switch network and the 2 way delay can be 10 seconds or higher. This large delay combined with the limited coverage seems to preclude the use of ARDIS for DGPS.

Motorola Data Plus is another SMRS, but it is designed to serve vehicle dispatchers. It is based on a network of base stations which Motorola installed for vehicle dispatch applications, and there are 500 trunk sites. Frequently, these antennas are located on 1200' buildings or 700' towers. Motorola

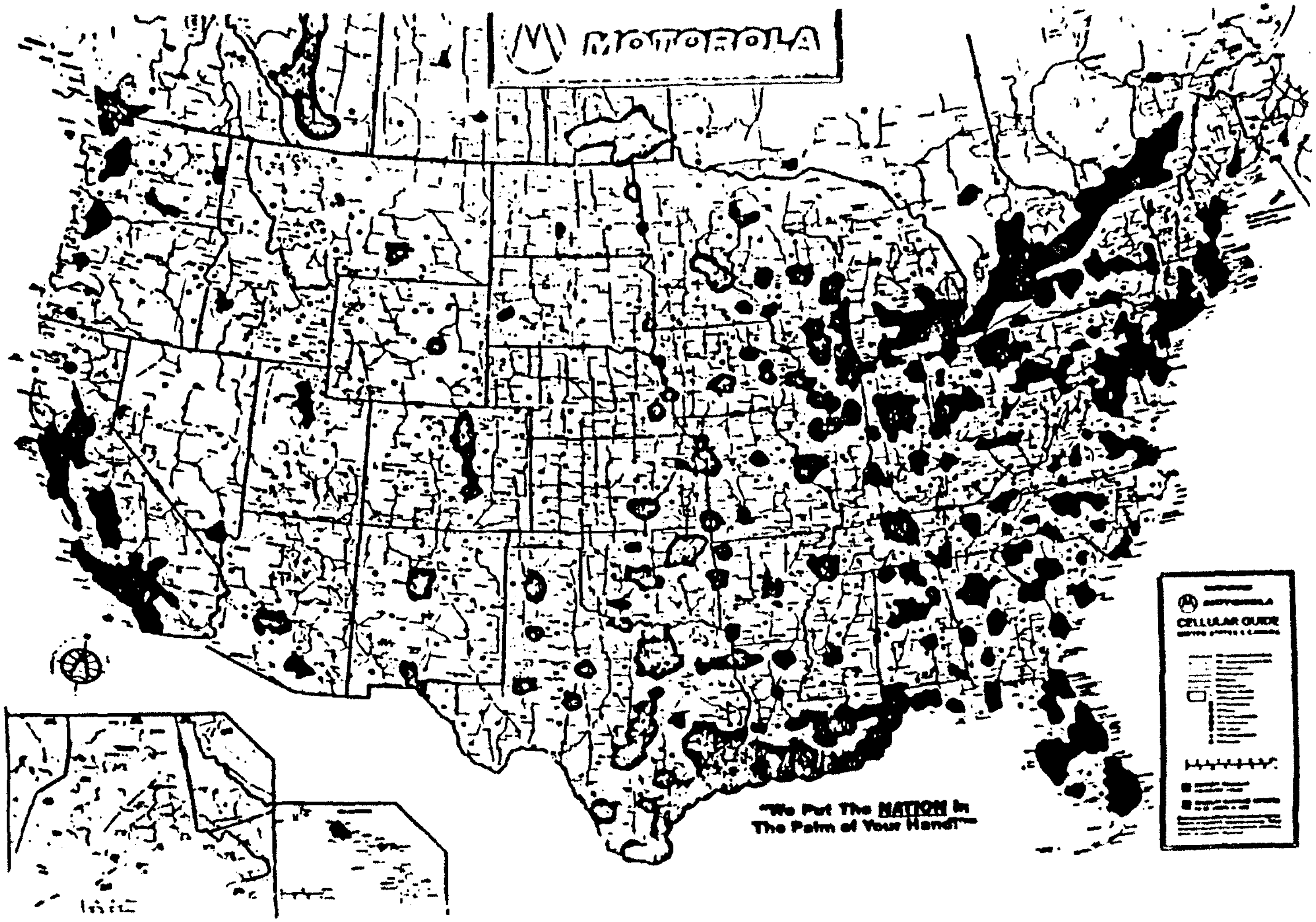

Figure 4.5: Cellular Telephone Coverage in the United States and Canada.

Data Plus covers 90% of the interstate highway system and approximately 60 to 70% of the land mass of CONUS.

The cost for using Motorola Data Plus is $0.05/packet, where each packet contains 240 8 bit bytes. Consequently, the cost for communicating meter level DGPS data for 22 eight hour days would be approximately $825/month. The cost for decimeter level DGPS would be approximately $33,000/month.

Unfortunately, Motorola Data Plus is another packet switch network and the delay can be greater than 10 seconds. For this reason, it does not seem well suited for DGPS broadcast.

4.6 FM Subcarrier

FM broadcast stations can broadcast data by placing a subcarrier 66 to 96 KHz above their main carrier. This service is called Special Commercial Authorization (SCA) and is used to broadcast "muzak", financial data (for Dow Jones) and news data (for Reuters). Additionally, Special Committee 104 of the Radio Technical Commission for Marine (RTCM) proposed FM subcarrier broadcast of DGPS information to automobiles.

Mainstream Data uses FM subcarriers and very small aperture satellite terminals (VSATs) to broadcast financial and news data to a nationwide network of fixed receivers, and they provided most of the information in this section. FM subcarriers are used to cover sites within 20 to 90 nautical miles of: Boston, New York, Philadelphia., Washington D.C., Atlanta, Miami, Chicago, Kansas City, St. Louis, Dallas, Salt Lake City, San Francisco, and Los Angeles. The FM SCA receiving equipment requires 30 Watts of power at 110 volts, and is approximately the size of a medium pizza box. FM broadcast to mobiles has been tried and suffers occasional shadowing.

The VSAT portion of the Mainstream broadcast uses the Kμ band and covers <u>rural</u> areas. The VSAT receiver includes a 0.75 meter dish and is not suitable for mobile use, because the antenna would be unable to track the satellite. However, a VSAT could be placed at fixed shore site and used with VHF/UHF link to the mobile. Their network is packet switched, but it includes a prioritized packet service, which can deliver data within 1 to 2 seconds.

The cost to broadcast priority packets over North America 24 hours/day depends on the data rate. If the data rate is 2400 bps, then the cost is $73,000 per month. For a data rate of 134.5 bps, the cost is $17,000 per month, and for a 50 bps, the cost is $8,000 to $10,000 per month.

If USACE wished to cover a local area with the broadcast from a single FM station, then the cost for a 19.2 K bps FM subcarrier is $16,000 to $21,000 per month. This cost includes a setup charge of $5,000 to $10,000, $6,000 per month to the station and $5,000 per month to lease the Mainstream transmitting and receiving equipment.

Nationwide broadcast of decimeter level DGPS data to USACE users using a mixture of FM and VSATs is expensive relative to TV VBI. Additionally, the broadcast of meter or decimeter level data using VSATs is awkward, because VSATs cannot be placed on mobile platforms. Leasing capacity on individual FM stations may make sense in special circumstances, but dedicated VHF or UHF equipment will probably be more cost effective in the majority of situations.

Section 5

Mobile Satellite Communications

5.1 Overview

Currently, mobile satellite services a. being developed at an extremely rapid rate. These will serve voice applications in aircraft, vehicles, and vessels which are outside of cellular phone coverage. Additionally, they will serve data applications for mobile users. The following companies are or will be the major providers of mobile satellite service in the United States:

- **Communications Satellites Corp. (COMSAT)**
- **American Mobile Satellite Corp. (AMSC)**
- **Qualcom**
- **John Chance (Starfix)**

COMSAT, John Chance, and AMSC will be discussed in some detail in Sections 5.2, 5.3 and 5.4.

Qualcom leases transponders or portions of transponders on satellites with domestic coverage. They use this capacity and their hub in southern California to provide two way communications to mobiles. They also provide a vehicle tracking service, which uses Loran-C as the position sensor. Qualcom is collaborating with DGPS Inc. of Houston Texas to provide DGPS broadcasts.

Geostar plans to launch their own satellites to provide a self contained (non GPS) position fixing service. However, they too would be willing to use their present system, which is based on leased capacity, to broadcast DGPS data.

Many new mobile satellite services are being considered. For example, Motorola has advanced a satellite concept called Iriduim, which consists of 77 low orbit satellites. This system would make worldwide communication from handheld terminals feasible, but it is just a concept at this time. In two years, the National Aeronautics and Space Administration (NASA) will launch the Advanced Communication Technology Satellite (ACTS). As shown in Figure 5.1, the ACTS satellite will have very small spot beams in the United States, and may result in practical systems for DGPS broadcast.

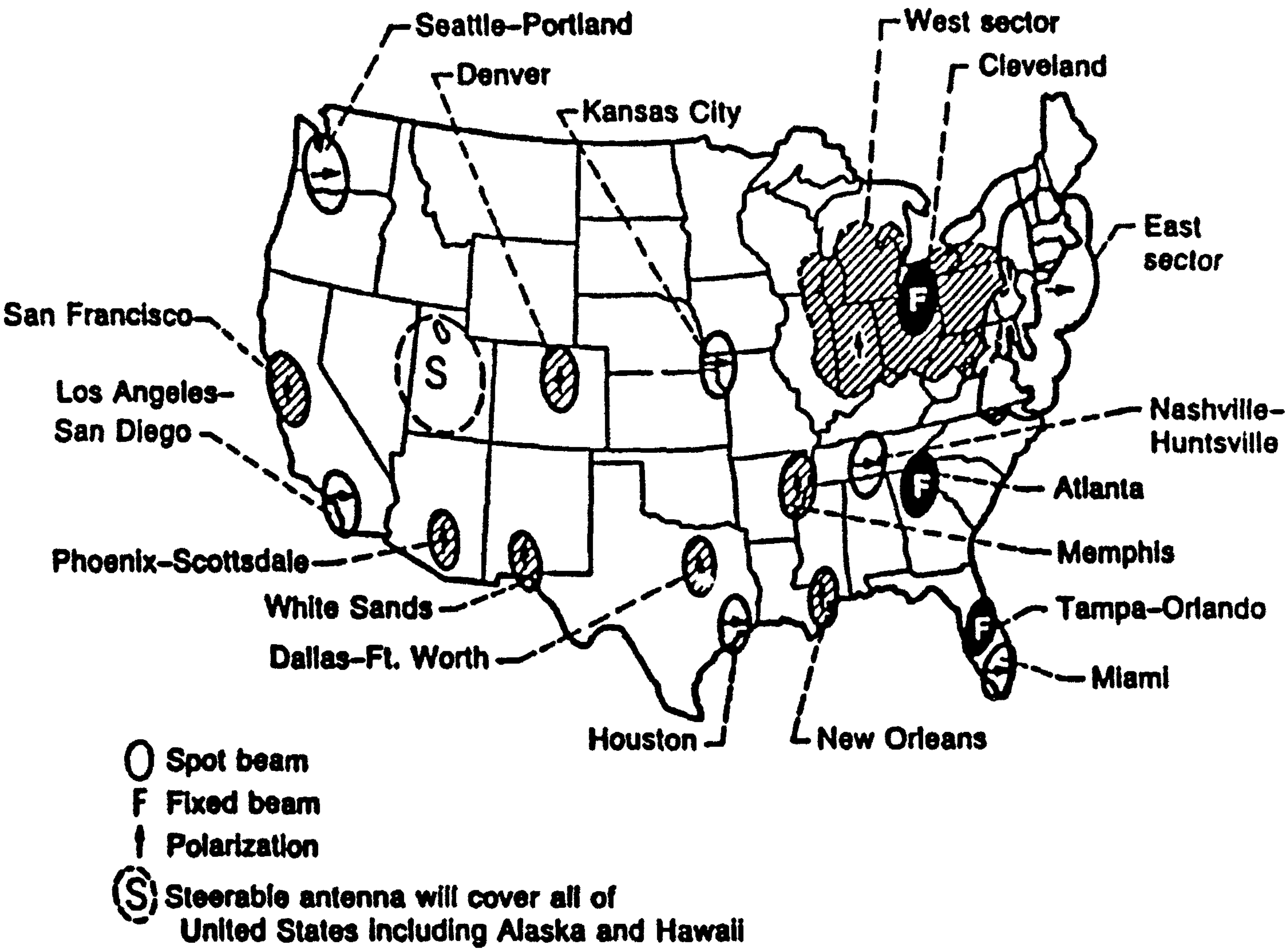

Figure 5.1: ACTS Multibeam Antenna Coverage .

5.2 Communications Satellite Corporation (COMSAT)

5.2.1 General Information

COMSAT is the U.S. signatory for the International Maritime Satellite Organization (Inmarsat), which launches satellites with hemispherical coverage. The Inmarsat system is depicted in Figure 5.2. As shown, mobile users are connected to land earth stations through the Inmarsat satellites. Only marine users are shown in the Figure, but Inmarsat can and will serve land mobile and airborne users as well. There are two land earth stations in the United States; one is located in Southbury, Connecticut and the other is in Santa Paula, California. These land earth stations are connected to the normal national and international phone systems. For example, a sailor can call home using the land earth stations, but Inmarsat calls cost $10 per minute. As shown in the Figure, distress calls are routed directly to rescue coordination centers.

The coverage footprints of the current Inmarsat satellites are shown in Figure 5.3. Recently, the Atlantic Ocean Region (AOR) satellite has been moved to the West to give better coverage of North America. Currently, Inmarsat is preparing to deploy their second generation of satellites (Inmarsat-2), and they are procuring their third generation (Inmarsat-3).

The cost of Inmarsat space capacity increases linearly with the required power, which means that satellite communication services are sensitive to the type of receiving terminal used by the mobile. This follows, because bigger terminals have more antenna gain, and thus require less satellite power to deliver the same quality of service. In fact, the G/T ratio of the terminal, which is the antenna gain (G) divided by the noise temperature of the entire terminal (T) is the key parameter.

The Inmarsat A terminal is the largest terminal and has the largest antenna gain; thus it is the cheapest to use. A light-weight, compact version of the Inmarsat A terminal is depicted in Figure 5.4. It weighs 75 pounds in total and includes a 1.2 meter dish. All Inmarsat A terminals are required to have $G/T = -4\ dB$, and the corresponding requirement on satellite power is around 9 dBW for a 2400 bps link. If the required bit rate is only 1200 bps, then the satellite power requirement drops by 3 dB to 6 dBW. The Inmarsat A terminal is the least costly to operate, but it does cost around $50,000 to purchase, and it cannot be used on small mobile platforms such as the skiffs used by some USACE districts. In these cases, the Inmarsat A terminal would have to be placed in a van, which would take a fixed position on the shore, and the DGPS data would be telemetered out to the small mobiles.

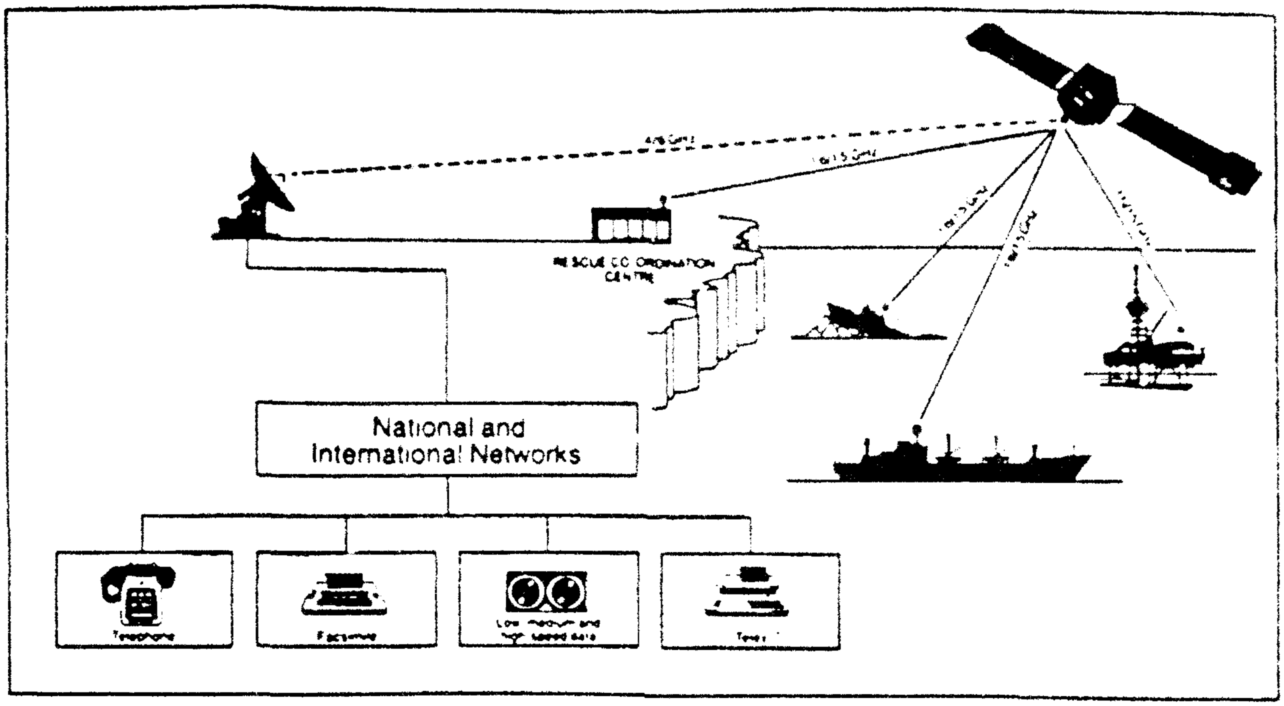

Figure 5.2: The Inmarsat System.

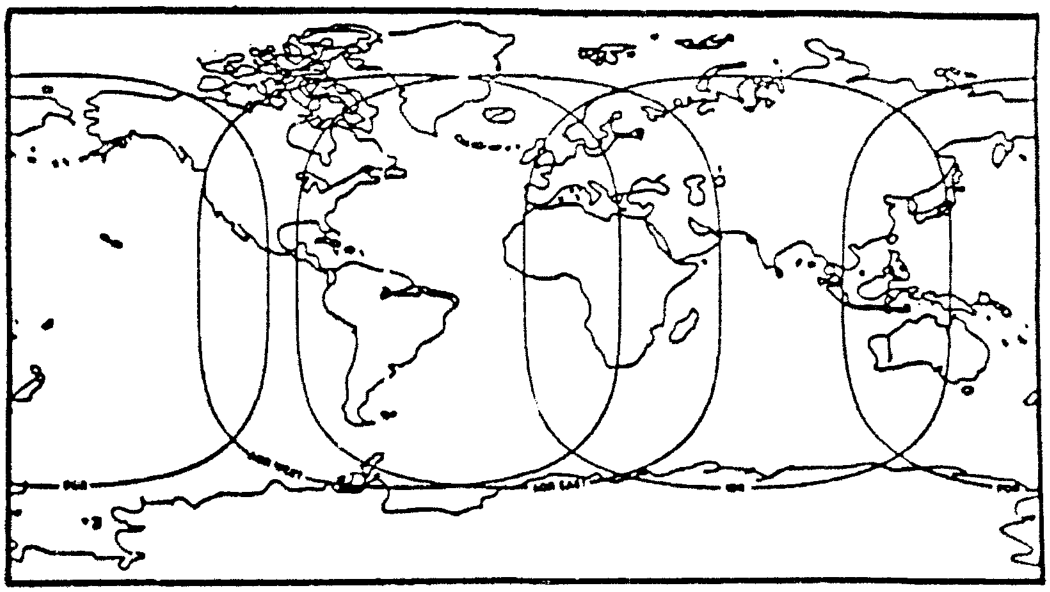

Figure 5.3: Coverage Footprints of the Current Inmarsat System.

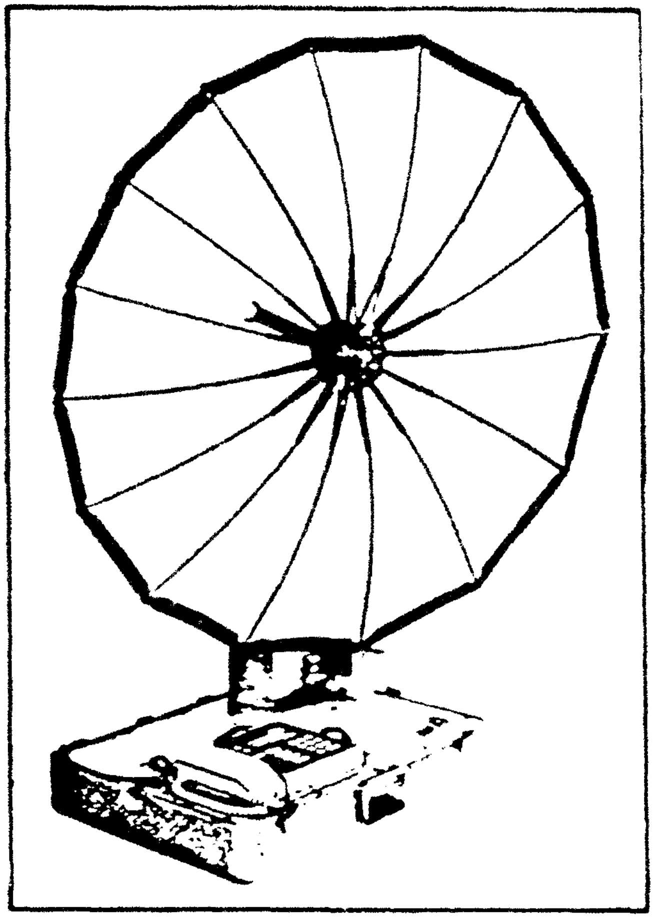

Figure 5.4: A Transportable Inmarsat-A Terminal.

Currently, an Inmarsat-M terminal is being developed. It is omnidirectional in elevation, but it scans in azimuth. Consequently, it has $G/T = -12\ dB$. It would require approximately 15 dBW of satellite power for 2400 bps. However, it would be suitable for mobile use even on small boats.

Finally, an Inmarsat-C terminal is nearing completion. This terminal is shown in Figure 5.5. It is omnidirectional in elevation and azimuth, which means that it is suitable for use on most any platform. However, it has $G/T = -25\ dB$, which means that around 27.5 dBW of satellite power would be required for 2400 bps.

5.2.2 DGPS Service

In May 1990, COMSAT announced a new DGPS service, which uses an Inmarsat satellite to broadcast corrections from a network of DGPS reference stations [11]. Initially, COMSAT will only have a single reference station located in Houston to serve oil related applications in the Gulf of Mexico.

COMSAT plans to provide a very reliable DGPS service. Two reference stations will be located at each reference site. Each reference site will have a leased line to the COMSAT land earth station, where the signal will be uplinked to the satellite for broadcast. In addition, the reference site will have a dialup capability in case the leased line fails. There are redundant uplink antennas at the land earth stations, and there is redundant capacity in space.

The cost of the complete DGPS service, including the COMSAT reference station network, is $500 per day per mobile if the customer purchases 1 to 60 days [12]. For days above 60, discounts are available. In all cases, the customer must supply the required Inmarsat A receiver, and the smallest and lightest Inmarsat A terminals cost around $50,000. Some larger versions cost significantly less.

The DGPS broadcast will be at 1200 bps, where each reference station will use about 100-150 bps on a time division multiplex basis. The customer may add his own reference stations to the Comsat network at no additional cost.

COMSAT is planning two additional but related DGPS services. First, they will store DGPS data for 60 days and make it available for an additional service charge. Second, they will make DGPS data available on a dial in basis. The customer can dial in over cellular, national or international phone lines, and access the DGPS data stream. A minimum charge would give a certain number of connect time, and additional connect time would be paid per minute.

Figure 5.5: Inmarsat C Terminal: Conceptual Model and Prototype .

Finally, COMSAT is investigating the viability of a DGPS service, which uses the much smaller and more convenient Inmarsat C terminals.

5.3 John Chance

John Chance leases capacity on 3 or 4 satellites because they broadcast their own spread spectrum ranging signals for position fixing. This position fixing service is called Starfix. They also piggyback a DGPS signal on the Starfix transmissions for quality control, and they charge around $1000 per day per mobile for the complete 24 hour a day position fixing service [13]. However, they will provide the DGPS service by itself for only $200 to $300 per day. This price may increase depending on whether or not the Starfix system continues to pay for fixed system costs such as the uplink. The DGPS service uses a data rate of 50 to 100 bps and provides 3 to 4 meter accuracy.

Currently, John Chance offers a new 6200A receiver, which is a 5 channel Starfix receiver that can receive the DGPS data. This terminal is smaller than their older receiver and may be acceptable for use on a 16' skiff or a small vehicle. The receiving antenna is a single horn array on an azimuth controlled platform. This antenna can track the satellite provided the mobile does not turn at rates greater than 30°/*second*. The antenna is inside a dome, which has a diameter of 20" to 24" and a height of approximately 24". It weighs around 25 pounds and only requires a flux gate compass to keep pointed at the satellites. The receiver occupies a 9" by 17" by 19" volume and weighs 75 pounds. It requires a keyboard and CRT terminal.

Soon, John Chance will release their new 3200 receiver, which is a single channel Starfix receiver that can receive the DGPS data. It is not much smaller or lighter than the 6200A receiver, but it will be somewhat less expensive. Additionally, John Chance is looking at a dedicated DGPS service for the future.

5.4 American Mobile Satellite Corporation (AMSC)

AMSC is a commercial consortium of Hughes Communications Mobile Satellite Services, McCaw Space Technologies, Mtel Space Technologies, Mobile Satellite Corporation, North American Mobile Satellite, Satellite Mobile Telephone Company, Skylink Corp. and Transit Communications. AMSC plans to launch satellites for mobile communications in 3 or 4 years. AMSC will receive reduced launch costs from NASA in exchange for some amount of free space capacity on early AMSC satellites. NASA plans to use this free capacity to find government applications, which would be well served by mobile satellite communications. NASA has collaborated with several government agencies including USACE, and they may well be able to receive free space capacity to test satellite

broadcast of DGPS data.

The AMSC system is shown in Figure 5.6. As shown, mobile users could be connected to the reference stations through the AMSC hub and satellite. The reference station would dial up the hub, and the mobile users would carry a small mobile satellite terminal.

AMSC will use 4 spot beams to cover CONUS; 1 spot beam to cover Alaska, 1 beam to cover Mexico, and 4 additional beams to cover Canada. These spots are shown in Figure 5.7, and are very well suited to DGPS. After all, DGPS data is not valid over areas larger than those covered by a single AMSC spot, so the broadcast of DGPS data over larger areas is intrinsically inefficient. In other words, if DGPS data is broadcast using much larger spots or hemispherical coverage, then the customer is paying for satellite power to broadcast data to locations where it cannot be used.

AMSC is planning to make a spectrum of user antennas available. First, an omnidirectional antenna is shown with a complete terminal in Figure 5.8 and this unit would be suitable for use on a small vessel or vehicle. It has a gain to noise temperature ratio of $G/T = -20\ dB$.

An antenna with a switchable vertical array is also being designed. It is flat and around 24" in diameter. It is omnidirectional in azimuth and directional in elevation angle. In fact, it can be switched to 2 or 3 vertical pointing angles. The switchable vertical array has $G/T = -17\ dB$.

Finally, a steerable antenna, which is omnidirectional in elevation and steerable in azimuth is being designed. This antenna can be mechanically or electrically steered in azimuth and is not much larger than the switchable vertical array. It enjoys a $G/T = -12\ dB$.

AMSC will lease satellite capacity to serve the decimeter (and meter) level DGPS applications. The annual lease costs for one spot coverage at 4800 and 2400 bps are given in Tables 5.1 and 5.2 respectively [14].

Antenna Type	G/T (dB)	EIRP (dB)	Annual Cost
Omni	-20	28	$350K
Switched	-17	25	$245K
Steered	-12	21	$105K

Table 5.1: Anal Lease Cost of AMSC Space Segment for 4800 BPS and One Spot: Unlimited Users.

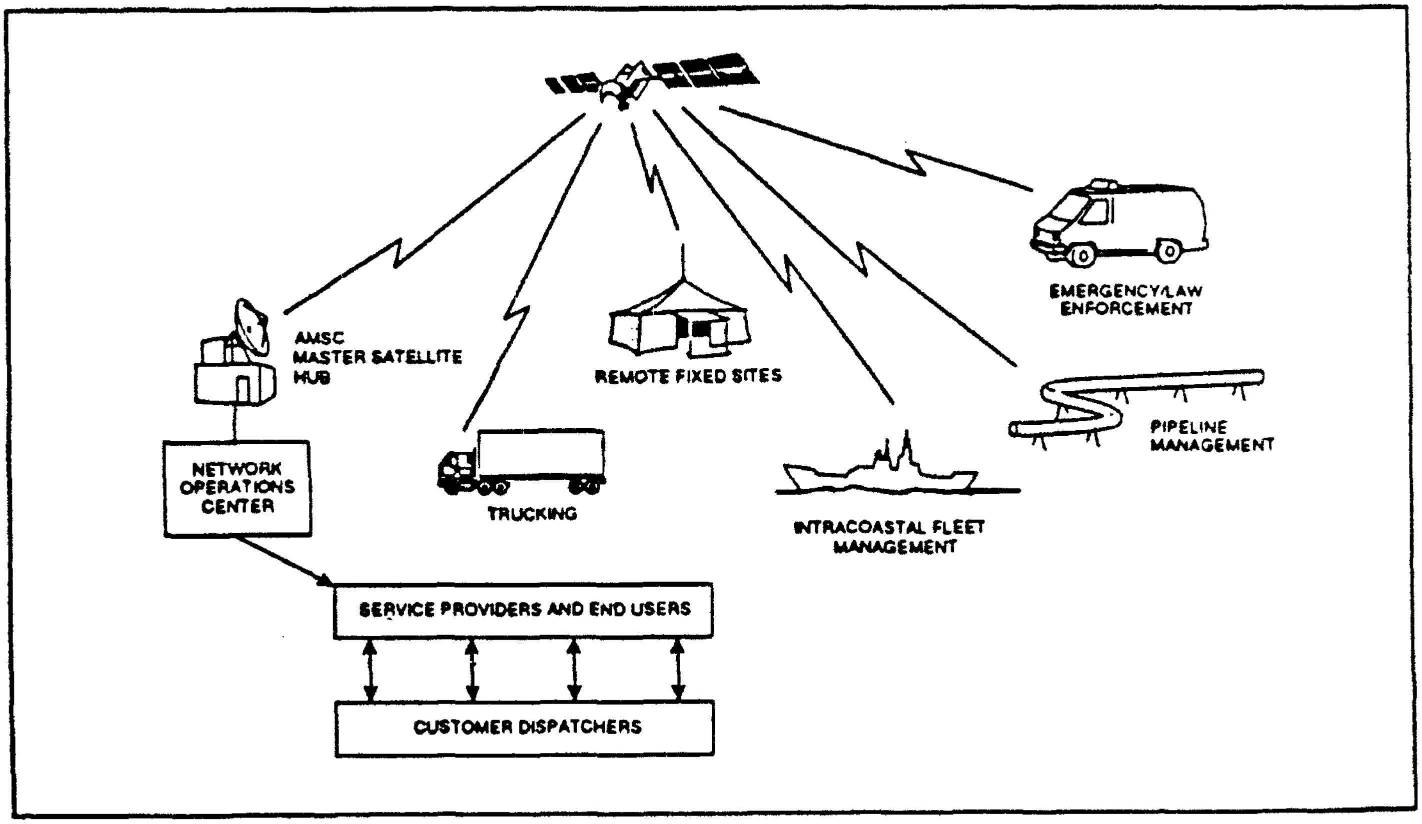

Figure 5.6: The AMSC Mobile Satellite System.

Figure 5.7: Spot Beam Coverage of the AMSC System.

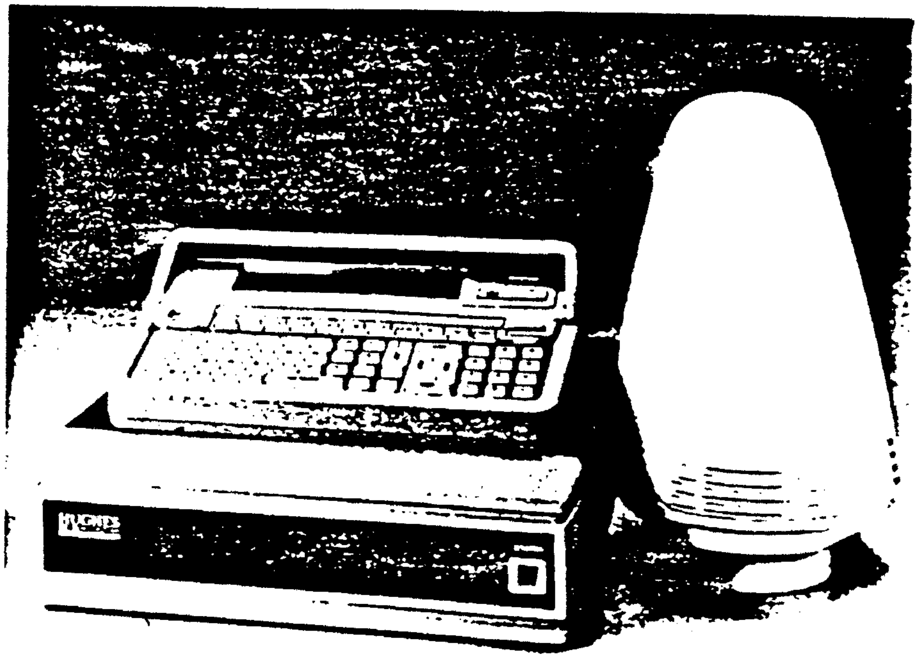

Figure 5.8: An AMSC Terminal With an Omnidirectional Antenna .

Antenna Type	G/T (dB)	EIRP (dB)	Annual Cost
Omni	-20	25	$245K
Switched	-17	22	$140K
Steered	-12	13	$90K

Table 5.2: Annual Lease Cost of AMSC Segment for 2400 BPS and One Spot: Unlimited Users.

Additional costs are:

- user terminals, which would be around $3000 each;
- cost of AMSC hub, which would be small compared to the space segment costs; and
- long distance charges from the reference station to the AMSC hub, which would be around $1000 per month.

At most, USACE would only need to develop interfaces between the reference station and the AMSC hub, and between the satellite terminal and the DGPS receiver.

A 4800 bps channel would be attractive, because time division multiple access could be used to send 2 to 4 decimeter level signals and several meter level signals. Such a combination should be more than enough to accommodate all the DGPS application in a given spot. The annual cost of $105,000 corresponds to only $8,750 per month. However, such a cost would only provide the DGPS corrections in a single spot, and 4 such spots or $35,000 per month would be required to cover the CONUS.

Nonetheless, we recommend that USACE attempt to participate in AMSC trials through NASA.

Section 6

Multiple Reference Stations

A decimeter level DGPS system requires a master reference station and two monitor reference stations. Tables 6.1 and 6.2 show the communications requirements and data rate requirements for the two types of reference stations [15]. As shown, the master reference station must communicate data to the mobile at 1000 to 2000 bps. In addition, the latency of the data should not exceed 1 second or so. In contrast, the monitor reference station only requires a data rate of 20 bps, and data latencies of 10 seconds are tolerable.

The communications requirements for the monitor reference station are very relaxed compared to those for the master reference station. First, the data rate is much lower and the tolerable latency is much greater. Consequently, the data from the monitor reference stations should be sent to the master reference station where it would be multiplexed onto the broadcast from the master reference station to the mobiles. Such a scheme is efficient, because it is much easier to deploy point to point communication systems than broadcast systems. With multiplexing, the monitor reference stations do not need to be connected to all the mobiles.

If possible, the monitor reference stations should be connected to the master reference stations using a phone line (see Figure 6.1). If the call is local, then a full time connection will cost a few hundred dollars a month. If the master reference station or the monitor reference station cannot be placed at a phone, then a VHF/UHF data link should be used to connect the reference stations to each other; or to connect the reference station to a facility with a phone (see Figure 6.2 and 6.3). The VHF and UHF equipment described in Section 4 would be appropriate for such a connection.

VARIABLE	RESOLUTION	RANGE	REQUIRED NO. OF BITS
L_1 Code Phase	0.1 m	$\pm$800 m	16
L_2-L_1 Code Phase	0.1 m	0-200 m	11
L_1 Carrier Phase	$\lambda_1/512$	0-$N_1\lambda_1$ m	19
L_2-L_1 Carrier Phase	$\lambda_2/512$	0-$N_2\lambda_2$ m	17
Satellite ID	----	32	5
Satellite Health	----	0-1	1
Time	1 msec	10 secs	16
Parity	----	----	6 bits/24 bits

Total Bits / Satellite = 106

Assume (worst case) 10 satellites $\Rightarrow$ 1060 bits/sec = <u>1.0 kbaud</u>

Table 6.1: Master Reference Station Communications Requirements.

VARIABLE	RESOLUTION	RANGE	REQUIRED NO. OF BITS
L_1 Code Phase	0.1 m	$\pm$48000 m	22
L_2-L_1 Code Phase	0.1 m	0-200 m	11
L_1 Carrier Phase	$\lambda_1/512$	$0\text{-}N_1\lambda_1$ m	25
L_2-L_1 Carrier Phase	$\lambda_2/512$	$0\text{-}N_2\lambda_2$ m	17
Satellite ID	----	32	5
Satellite Health	----	0-1	1
Time	1 msec	600 secs	22
Parity	----	----	6 bits/24 bits

Total Bits / Satellite = 116

Assume (worst case) 10 satellites $\Rightarrow$ 1160 bits/60 secs = <u>0.02 kbaud</u>

Table 6.2: Monitor Reference Station Communications Requirements.

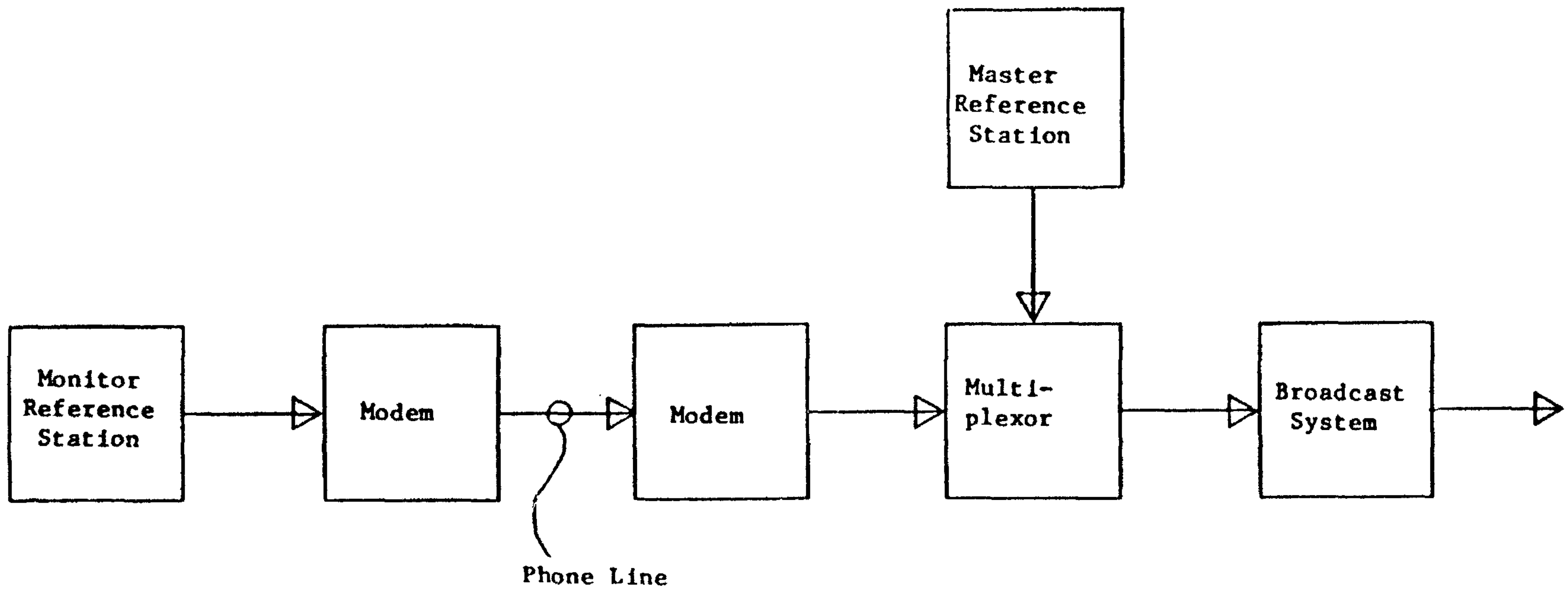

Figure 6.1: Monitor Reference Station to Master Reference Station Using a Phone Line.

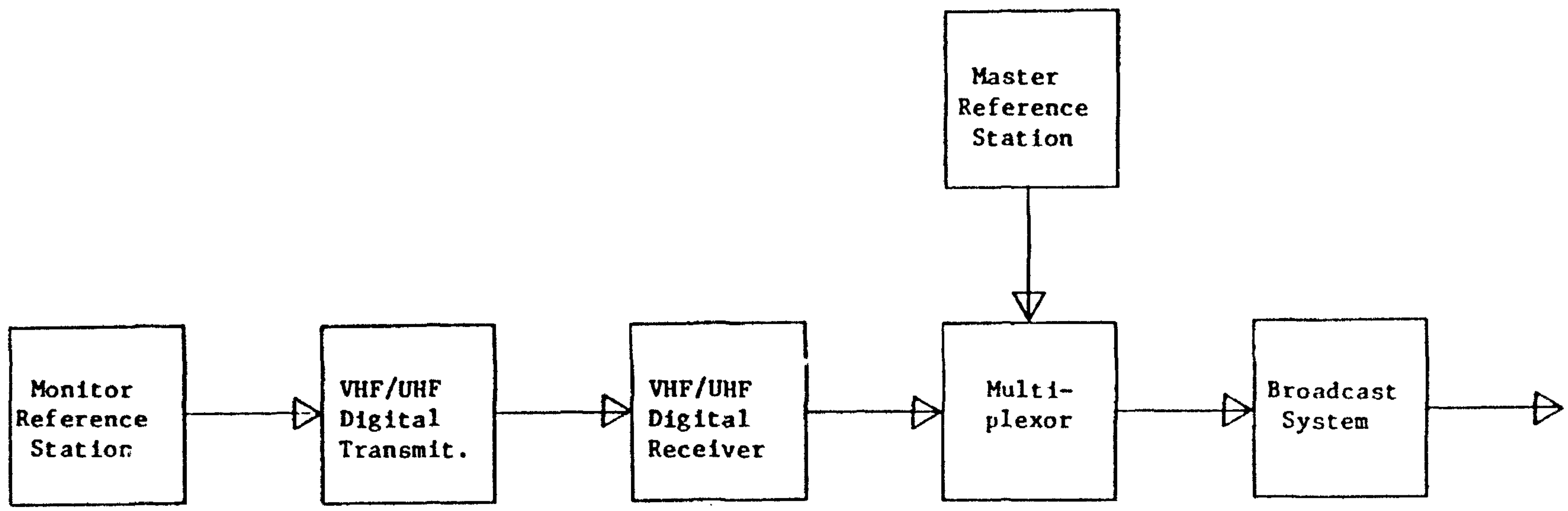

Figure 6.2: Monitor Reference Station to Master Reference Station Using a VHF/UHF Data Link.

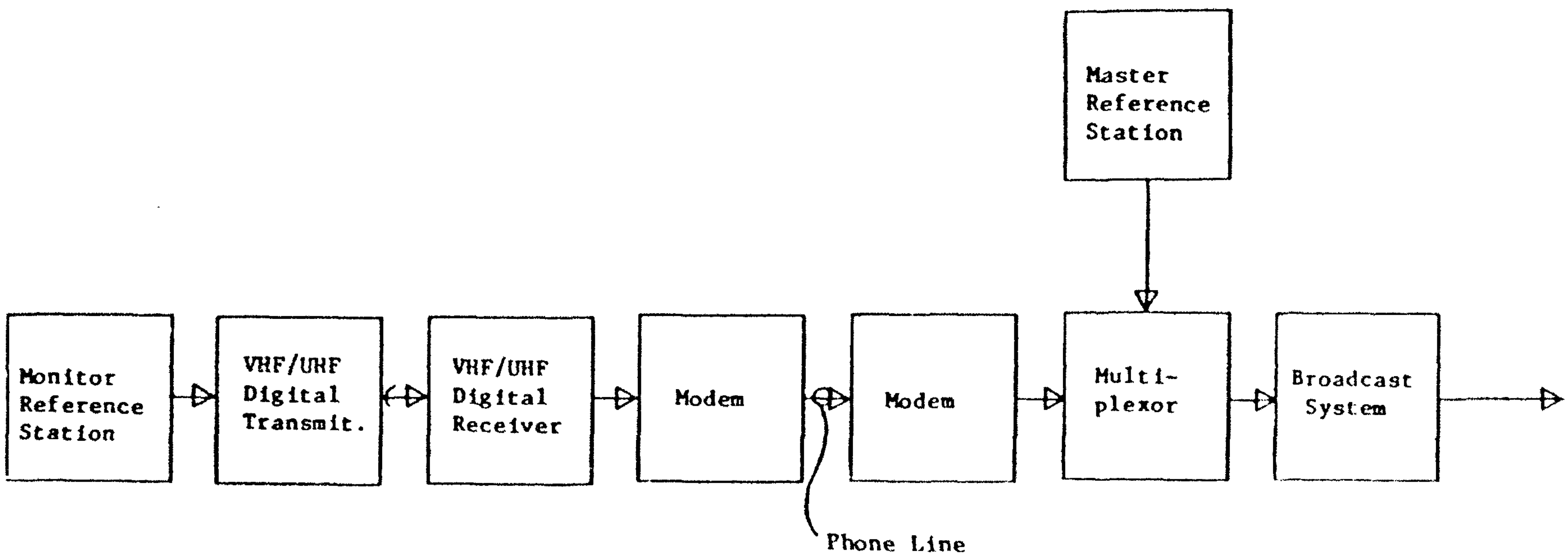

Figure 6.3: Monitor Reference Station to Master Reference Station Using a VHF/UHF Data Link and a Phone Line.

Section 7

Radio Channel Licensure

This section briefly describes the process whereby agencies of the U.S. government obtain new radio channels. It is based on discussions with the Marine Radio Policy Branch of the U.S. Coast Guard. The procedure for USACE may differ. The description assumes that the desired radio channel falls in a government band, because the licensure of channels in the non-government band is very difficult unless the government can demonstrate that the new system will provide a public service. Further, this Section does not describe the licensure of new channels in the shared (government and non-government) bands, because such a procedure is more complicated than the one for government bands.

First, the radio frequency manager and the cognizant technical personnel develop or obtain a description of the desired channel including: frequency, radiated power, location, antenna type and pattern, modulation, transmitter and receiver nomenclature, and whether or not any special or new equipment is being purchased. If this channel description corresponds exactly to a channel for which the agency is already authorized, then the agency may start transmitting. However, if the desired channel is not currently assigned to the agency, as in the majority of cases, then the agency must apply to the National Telecommunications and Information Administration (NTIA). The radio frequency manager is familiar with the process of obtaining a frequency allocation including where to apply and what information will be needed.

If a new channel is required, then the requesting agency forwards a complete description of the desired channel to the NTIA. Usually, the requesting agency will informally approach other agencies and coordinate the request before formal application. The description should contain all information required for the analysis of potential interference. The effort described is known as a site survey, and it is usually completed by the radio equipment supplier.

If the radio channel request is associated with a major purchase of equipment, then it is forwarded to the Special Plans Subcommittee of NTIA. If no large equipment purchase is involved, then the request goes to the Frequency Assignment Subcommittee (FAS) of the NTIA. The latter case is considered in this Section.

The frequency manager of the FAS uses the information supplied by the requesting agency to generate a data sheet, which is circulated to all member agencies of the NTIA. All the other agencies review the channel request for interference potential. If interference is likely, then the concerned agencies try and

find a solution and revise the original channel request. Finally, all the agencies vote on the channel request, and if that vote is positive, then transmission may begin.

The time from the formal application to the vote is between 30 and 90 days, unless difficulties are encountered. If the requested channel differs only slightly from channels for which the agency is already authorized, then the procedure can be much quicker.

REFERENCES

[1] P.K. Enge, R.M. Kalafus and M.F. Ruane, "*Differential Operation of the Global Positioning System*," IEEE Communications Magazine, vol.26, no.7, July 1988.

[2] International Telecommunications Union, "*Final Acts of the Regional Administrative Conference for the Planning of the Maritime Radionavigation Service (Radiobeacons) in the European Maritime Area*," Geneva, 1986.

[3] J. Quill, "*U.S. Coast Guard Differential GPS System Development*," Proceedings of the RTCM Annual Meeting, May 1986.

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[14] American Mobile Satellite Corporation, private communication, August 1990.

[15] Trimble Navigation Limited, private communication, August 1990.

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CCIR Recommendation 435-3, "*Prediction of Sky-Wave Field Strength Between 150 and 1600 kHz*", ITU, Geneva, 1978.

CCIR Report 575-1, "*Methods for Predicting Sky-Wave Field Strengths at Frequencies Between 150 kHz and 1600 kHz*", ITU, Geneva, 1978.

Rockwell Collins, private communication, June 1990.

Appendix A

Annotated Bibliography on DGPS Communications

Differential GPS Communication Techniques

Post-Processing Methods:

Reference	Organization	Environment	Comments
"Codeless GPS for Positioning of Offshore Platforms and 3D Seismic Surveys" MacDoran, et al (Red Book III)	ISTAC, Inc.	Marine, Helicopter	Uses SERIES technique, Measure L1 and L2 phases to account for Ionospheric Effects Accuracy: 20 cm after 6 min observation, 20 m baseline
"Civil Helicopter Flight Operations Using Differential GPS" Edwards and Loomis (Red Book III)	NASA Ames Research Center	Airborne, Civil Helicopter	DGPS Method: Corrected Pseudo-ranges Corrections made to C/A code Accuracy: From 40 m (conventional GPS) to 6.4 m (DGPS)
"Differential GPS-Tests with L1 C/A-Code Receiver" Borcherding and Bultman (GPS-88)	Prakla Seismos AG (FRG)	Stationary & low dynamics (Automobile)	Ground Truth corr. to C/A code on L1 (Use same 4 SV's) Stationary Accuracy of 4 m achieved Mobile Accuracy: ~ 10 m
"Practical Aspects of Kinematic Surveying" Eschenbach, et al (GPS-88)	Trimble Nav.	Kinematic Surveying (land based)	Accuracy ? Standard Deviation: Centimeter-Level
"High-Precision Kinematic GPS Differential Positioning: Exp., results, integration with Ring Laser Inertial Sys" Hein, et al (GPS-88)	IAPG, Univ. FAF Munich (FRG)	Land, Shipborne, and Airborne Kinematic Surveys	Phase smoothed, P-code with Pseudo-range corrections on L1 and L2 with phase differencing tests. Land accuracy = 3 cm Airborne: decimeter accuracy Integration of Ring Laser Gyro (in case of Loss of Lock): ~ 3 cm const. acc.
"A Test of Airborne Kinematic GPS Pos. for Aerial Photography: Methodology" Keel, et al (GPS-88)	Nortech Surveys, Inc. (Canada)	Aerial Photography	Phase Smoothed Pseudo-ranges for P-code using L1 and L2 Pseudo-range corrections update rate = 30 sec, Baseline = 20 km Accuracy: 1 meter
"Applying Kinematic GPS to Airborne Laser Remote Sensing" Krabill, et al (GPS-89)	NASA	Airborne LIDAR	Uses L1 carrier phase measurements Problems with INS prevented expected decimeter accuracy, however, about 1 meter accuracy was attained

Post-Processing Methods:

Reference	Organization	Environment	Comments
"Real Time Differential GPS and Postproc. Accurate Trajectories Recovery: An Update of Methods and Results" Nard, et al (GPS-89)	SERCEL	Mobiles, Airplanes	"MISSION" and "TRAJECTORY" postprocessing packages Phase smoothed pseudo-ranges: Accuracy -> .5 m Double Differenced carrier phase method: Accuracy -> 10 cm
"Developments in Use of GPS As Range TPSI" Abbey (GPS-87)	General Dynamics	Aircraft TSPI info.	Integrated GPS/INS navigation system C/A-Code pseudo-range corrections error = 2 m rms
"GPS-Based Geodesy in California, Mexico and the Caribbean" Melbourne, et al (PLANS-86)	JPL	Tectonic Geodesy	C/A-Code and carrier phase processing Network Configuration: over 245 km baseline 3D rms accuracy ~ 5 cm
"Effects of the Ionosphere on GPS Relative Geodesy" Henson & Collier (PLANS-86)	TI	Land, Static Surveying	Double Differenced carrier phase measurements on L1 and L2 over 350 km Accuracy: 1 m
"Three-Coordinate Positioning Within 1 Part in 10 Million Without GPS Codes" Ladd (PLANS-86)	Western Geophysical Co. of America	Static Surveying	Double Differenced carrier phase measurements on L1 and L2 784 m baseline 3-D accuracy: millimeter level
"High Precision Differential GPS Navigation" Kleusberg & Wells (PLANS-86)	Geodetic Research Lab, U of New Bruns.	Land, Kinematic Surveying	P-code corrections Baseline of 95 km Accuracy: 1.7 m rms
"Use of Phase Data For Accurate Differential GPS Kinematic Positioning" Lachapelle, et al (PLANS-86)	Canadian Hydrographic Surveys	Land Kinematic Positioning	P-Code or C/A-Code with carrier phase on L1 and L2 1000 km baseline 1-3 m rms accuracy
"High Precision Survey Results Using The Ashtech XII GPS Receiver" Remondi (PLANS-88)	Ashtech, Inc.	Land-based surveying	Double Differenced carrier phase measurements on L1 baseline of 105 km Positional accuracy: 1.5 ppm (16 cm)
"Control Surveys for British Columbia Terrain Resource Info. Management Prog." Hlasny & Schleppe (PLANS-88)	McElhanney Geosurveys	Land-based static surveying	C/A-Code on L1 100 km baseline Positional accuracy: 2 m

Post-Processing Methods:

Reference	Organization	Environment	Comments
"Applying Kinematic GPS Techniques At Our Nations's Airports" Remondi (PLANS-90)	NGS/NOAA	Land-based kinematic surveying	determine RunWay EndPoints (RWEP's) using carrier phase observables cm level accuracy over baseline < 2 km
"Determination of Precise Position of a Moving Vehicle With GPS" Goad (PLANS-90)	Ohio State U.	Land-based kinematic surveying	double differenced carrier phase observations decimeter accuracy
"Experiments for an Integrated Precise Airborne Navigation & Gravity Recovery System" Hehl & Ertel (PLANS-90)	Univ. FAF, Munich	Airborne Gravity Experiments	Baseline: 300 km Differential Method: ? Accuracy: ?

Line of Sight Methods:

Reference	Organization	Description of Communication	Power and Range	Environment	Tracking System	Comments
"Differential GPS-Tests with L1 C/A-Code Receivers" Borcherding and Bultman (GPS-88)	Prakla Seismos AG	VHF (voice chan) 50 bps, f = ? RTCM SC-104	35 W (shared voice system) max 25 miles during tests		Helicopter Positioning Information	Corr.s sent through modem over voice chan Accuracy determined after test flights to be better than 7m
"Vehicle Navigation Using Differential GPS" Hunter, et al (GPS-89 & PLANS-90)	Ashtech, Inc.	Bi-dir UHF link f = 462.5 MHz 2400 bps	P = ? distance for tests = 4.5km			Corrected Pseudo-Range to C/A code, Integrated with "Dead Reckoning" Speed and directional sensors and map matching Accuracy: 1-2 m
"Helicopter Terminal Approach Using Differential GPS with Verticle-Axis Enhancement" Edwards, et al (GPS-87)	NASA Ames Research Center	VHF link, f = ? Two-Way Link RTCM SC-104 format	30 W 160 km		Airborne Position, Vel & Attitude Info	C/A-Code pseudorange corrections Integrated with baro. altimeter & vert. accelerometer, hardware problems with Ref. Rec., back-track real-time results & adjust with postprocessing: 6.6 m rms 3D
"Integration of Differential GPS with INS for Precise Positioning, Attitude and Azimuth Determination" Aggarwal (GPS-87)	Magnavox	VHF, f = ? 1200 bps modem Update= 2SV/sec RTCM SC-104	? 1 km during tests		Marine, dynamic oper.	Integrated with INS navigation system P-Code corrections on L1 and/or L2 Position: 5m, Velocity: 0.3 m/s, & Attitude: ~1 mrad
"Status of United States Coast Guard Sponsored Differential GPS Demonstration System Development" Pietraszewski, et al (GPS-87)	USCG	UHF link, f = ? RTCM SC-104 format	65 W 70 nmi		Airborne	C/A-Code pseudorange corrections Satisfy 8-20 m 2 DRMS accuracy goal specified in the FRP.
"Development Of A New Data Link For The GPS Range System" Quick, et al (PLANS-90)	QUALCOMM & Interstate Elec.	L-band, f = ? Bi-dir comm. link, TSPI BW = 1.6 MHz				C/A-Code Pseudorange corrections Accuracy: ?
				Airborne		
				Land Vehicle		

LF/MF/HF Methods:

Reference	Organization	Description of Communication	Power and Range	Environment	Comments
"Sea Trials, Message Delay, and Network Design for DGPS Radiobeacons" Ruane, Enge, et al (GPS-89)	USOG	f = 300 kHz diff. update rates RTCM SC-104	1.5 W (emrp) 200-500 km	Marine, Harbor Nav.	USCG R&D center conducted tests to observe effect of update rate on accuracy (Fig.1)
"Real Time Differential GPS and Postproc. Accurate Trajectories Recovery: An Update of Methods and Results" Nard, et al (GPS-89)	SERCEL	dual f: 1.6 Mhz & 3.5 MHz, 50 bps RTCM SC-104	2, 100 W transmitters, 800 km	Marine tests	Corrected Pseudo-range for C/A-code Update rate: 4.2 sec for 5 SV's, or 8.1 sec for 10 SV's Accuracy: 2-3 m
"DIFFSTAR - A Project Based on Differential GPS in Northern Norway" Herving (PLANS-86)	A/S Kongsberg Vaapenfabrikk	f = 300 kHz 12-14 sec update RTCM SC-104	3000 W 1000 km	Marine, Oil Platforms, Seismic tests	C/A-Code pseudo-range corrections, time averaged tests on 570 km baseline: 4 m rms acc.
"Reliable High Accuracy Long Range Real Time Differential GPS Using a Lightweight High Frequencies Data Link" Nard (PLANS-86)	SERCEL	Three HF transmitters: 1.6 MHz-16 MHz RTCM SC-104	1500 km	Marine Applications	C/A-Code corrections with carrier phase frequencies transmitted depend on MUF Expect to get 1 m accuracy over 1000 km
"Sercel High-Precision Real-Time Diff. GPS Principles and Results" Nard & Gounon (PLANS-88)	SERCEL	3 HF Xmitters: 1.6-16 MHz RTCM SC-104 Update rt.< 6 sec	100 W each 500-2000 km	Marine Applications	C/A-Code corrections with carrier phase frequencies transmitted depend on MUF Accuracy: 0.5 m over 500 km baseline

Pseudolite DGPS Methods: Spread Spectrum on L1 carrier, 30 mW, 50 km range.

Reference	**Organization**	**Environment**	**Comments**
"The Application of NAVSTAR Differential GPS in the Civilian Community" Beser and Parkinson (Red Book II)	Intermetrics	Airborne, Helicopter	Ground Truth Differential Corrections Tests at YPG Accuracy: From 20-40m (conventional) to 5m (DGPS), 10 km baseline
"Global Positioning System Differential Navigation Tests at Yuma Proving Ground" Krczynski, et al (Red Book III)	U.S. Air Force	Helicopter Dynamic Tests	Corrected Pseudo-range method of DGPS Corrected C/A and P codes Accuracy: 2-3 m with updated corrections, 10-13m with old corrections
"Pseudolite-Aided GPS. A Comparison" Stein & Tsang (PLANS-88)	Science App's. International	Static, & Low dynamic land positioning	Accuracy: 5.61 m

Satellite Methods:

Reference	**Organization**	**Description of Communication**	**Power and Range**	**Environment**	**Comments**
"Long Baseline Differential GPS Results via Starfix Data Link" Ott (GPS-89)	Starfix Div., John E. Chance & Associates	10 bps, over Starfix satellite links (4)	U.S. ?	Offshore Oil platforms and other uses	Long baselines in U.S. 1000 - 3000 km Corrected Pseudo-ranges to C/A-code Accuracy obtained: 5.8 m rms

Other Methods

Reference	Organization	Description of Communication	Power and Range	Environment	Comments
"Performing Centimeter-Level Surveys in Seconds with GPS Carrier Phase: Initial Results" Remondi (Red Book III)	National Ocean Service, NOAA	?	?	Roving Land Antenna, Surveyed Points	Uses Carrier Phase measurements, Triple difference, ~400 m baseline, Accuracy: centimeter-level in seconds
"Differential GPS with a Sequencing Receiver" Eschenbach & Tiwari (GPS-87)	Trimble Nav.	Hardwired to computer over RS232 data link RTCM SC-104	short baseline ~ 12 m	land, static surveying	Ref.Receiver and user are connected to same computer for real-time processing. 2 channel slow sequencing receiver 2.3 m rms error on 12 m baseline
"GPS Differential Positioning Technologies For Hydrographic Surveying" Falkenberg, et al (PLANS-88)	Nortech	? RTCM SC-104	?	Hydrographic Surveying	L1 C/A-Code pseudorange corrections plus carrier phase Accuracy: 5 m
"GPS Solves The Air Combat Training Problem" Hoefener & Van Wechel (PLANS-90)	Interstate Elec.	?	?	Air Combat Training Position Info.	Differential P-Code w/ inertial aiding 100 km baseline 4.5 m 3D rms accuracy

Waterways Experiment Station Cataloging-in-Publication Data

Enge, Per K.
Investigation of real-time Differential Global Positioning System (DGPS) data link alternatives / by Per K. Enge, Keith Pflieger ; prepared for Department of the Army, U.S. Army Corps of Engineers ; monitored by U.S. Army Topographic Engineering Center.
93 p. : ill. ; 28 cm. — (Contract report ; DRP-92-7)
Includes bibliographical references.
1. Global Positioning System. 2. Real-time control. 3. Telecommunication systems. I. Pflieger, Keith. II. United States. Army. Corps of Engineers. III. U.S. Army Topographic Engineering Center. IV. U.S. Army Engineer Waterways Experiment Station. V. Dredging Research Program. VI. Title. VII. Series: Contract report (U.S. Army Engineer Waterways Experiment Station) ; DRP-92-7.
TA7 W34c no.DRP-92-7